# ALACHUA COUNTY SOUTHWEST LANDFILL GAS PRODUCTION AS A FUNCTION OF TIME

BY
GERALD ROLLIN MANLEY

A NON-THESIS PROJECT PRESENTED TO THE
DEPARTMENT OF ENVIRONMENTAL ENGINEERING SCIENCES OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF ENGINEERING

MAY 1992

## ACKNOWLEDGEMENTS

I thank my committee chairman, Dr. W. Lamar Miller and the committee members, Dr. Paul Chadik and Dr. Jonathan Earle for their support of this research project. I thank Dr. Ann Wilke for the use of her references and rotameter.

I thank Mr. Tim Townsend for providing his guidance, assistance, wit and wisdom throughout my research. I thank Ms. Diane Dwyer and Mr. Eduardo Smith for sharing in our labor and research efforts. I thank Mr. George Jennings and all the members of the ACSWL team for the many "rides to the top of the hill".

A special appreciation and acknowledgement goes to my family and friends for there lasting support, love, and companionship. I thank my wife, Cathy, and daughter, Jenna, for their endurance, backing and devotion through this ordeal.

TABLE OF CONTENTS

APPENDICES PAGE

LIST OF TABLES

## LIST OF FIGURES

# CHAPTER 1

## INTRODUCTION

Refuse disposal is an issue that must be addressed by virtually every community in the country. In the last twenty years, the demand for disposal techniques that minimize impact on the environment has increased. In addition, there has been a heightened interest in energy recovery from wastes as a method to reduce both the cost of waste disposal and national dependence on foreign energy supplies.

The most common method of solid waste disposal in the United States is the utilization of sanitary landfills (Barlaz et al. 1990, DeWalle et al. 1978, Esmaili 1975, Ham et al. 1979, Miller et al. 1991a). Landfilling remains an economically viable method of solid waste disposal. DeWalle et al. (1978) indicated that alternative means of disposal have often proven to be less effective in terms of both cost and in meeting solid waste disposal demands.

Franklin Associates (1988) estimated that 80% of the nation's municipal solid waste (MSW) stream was disposed of in sanitary landfills in 1987. Porter (1988) reported a higher approximation of 90%. The Florida Department of Environmental Regulation (1991) reported the disposal of an estimated 13.4

million tons of MSW in landfills which equates to 69% of the state's waste stream.

Gas production in sanitary landfills is a subject of much concern. Uncontrolled landfill gas (LFG) migration and emission poses a potential explosion hazard, may acidify groundwater, contain malodorous and potentially harmful compounds, and contribute to the greenhouse effect (Miller et al. 1991b). Methane ($CH_4$) and carbon dioxide ($CO_2$) are the most common gases released.

Methane is the primary terminal product of a series of biologically mediated reactions involved in refuse decomposition within the sanitary landfill system (Barlaz et al. 1989). Methane constitutes between 40 and 60 percent of (LFG). Methane is explosive in air at concentrations between 5 and 15 percent (Esmaili 1975, Schumacher 1983, Tchobanoglous et al. 1977). However, there is no danger that a landfill will explode because there is little or no oxygen in a landfill when methane concentrations reach this critical level.

The remaining volume of LFG is primarily $CO_2$ and 1 or 2% (total) of other miscellaneous inorganic gases and organic vapors. Carbon dioxide is troublesome because of its density. $CO_2$ is about 1.5 times as dense as air and 2.8 times as dense as methane; thus it will tend to move downward, through the refuse and possibly any underlying formation until it reaches the groundwater. Because it is readily soluble in water, $CO_2$

will usually lower the pH, which in turn can increase the hardness and mineral content of the groundwater through solubilization.

The first significant interest in the management of LFG began in the early 1970s when it was realized that there was sufficient energy value in LFG to justify purifying it to produce a quality gas for sale to utility companies (Rice 1989). The driving force in LFG development at that time was the potentially large profit from the sale of the gas in a time of rapidly rising oil prices triggered by the "energy crisis" of 1973. In late 1985, after nearly a decade of growth, the energy recovery side of the LFG industry experienced a sharp decline with the collapse of world energy prices.

The impact of environmental regulations and the growing need to effectively control the odor and migration of landfill gas has, once again, given considerable impetus to the study and development of landfill gas recovery, processing and utilization. In addition to being a usable energy source, methane production has several other advantages as described by Barlaz et al. (1990). After the onset of methane production, a reduction in leachate strength can be expected, possibly leading to lower leachate treatment costs and a reduced risk to groundwater contamination. A second advantage is the potential to reduce costs or even gain profits from gas control through gas recovery and utilization. Finally, most

of the settlement, or stabilization, of a landfill can be expected by the end of the refuse decomposition period. Enhanced refuse decomposition and its concomitant landfill gas production will lead to a reduction of long-term care requirements for gas migration and landfill cover maintenance.

The objective of this report is to determine the landfill gas production rate of the Alachua County Southwest Landfill, with the emphasis placed on $CH_4$ and $CO_2$, as a function of time. While it is recognized that difficulty exists in the prediction of the amount of gas available and recoverable from a landfill, such analyses are essential to the development of economically sound projections for LFG recovery.

# CHAPTER 2

## SITE DESCRIPTION

The Alachua County Southwest Landfill (ACSWL) consists of approximately 145 acres. It is located in Alachua County in North Central Florida approximately two miles southwest of Archer (see Figure 2-1) along Florida Highway 24 (Latitude 29° 30' 40" N, Longitude 82° 32' 50" E). The surrounding area is predominately agricultural. The landfill began operation in late 1973 and is currently the only active landfill in the County (CH2M Hill, 1986).

As shown in Figure 2-2, the site consists of three separate landfill units: one lined and two unlined. The oldest unlined unit received MSW from November 1973 until December 1985 when it was closed and capped. The second unlined unit received MSW from December 1985 until May 1988 when it too was closed and capped.

The third and active unit is a lined Class I landfill which began receipt of MSW in April 1988. A Class I landfill is defined by the Florida Department of Regulation as one that receives in excess of 20 tons of MSW on a daily basis. This unit is surrounded by a large earthen berm and is lined on the bottom and sides. The liner is a composite of one foot of

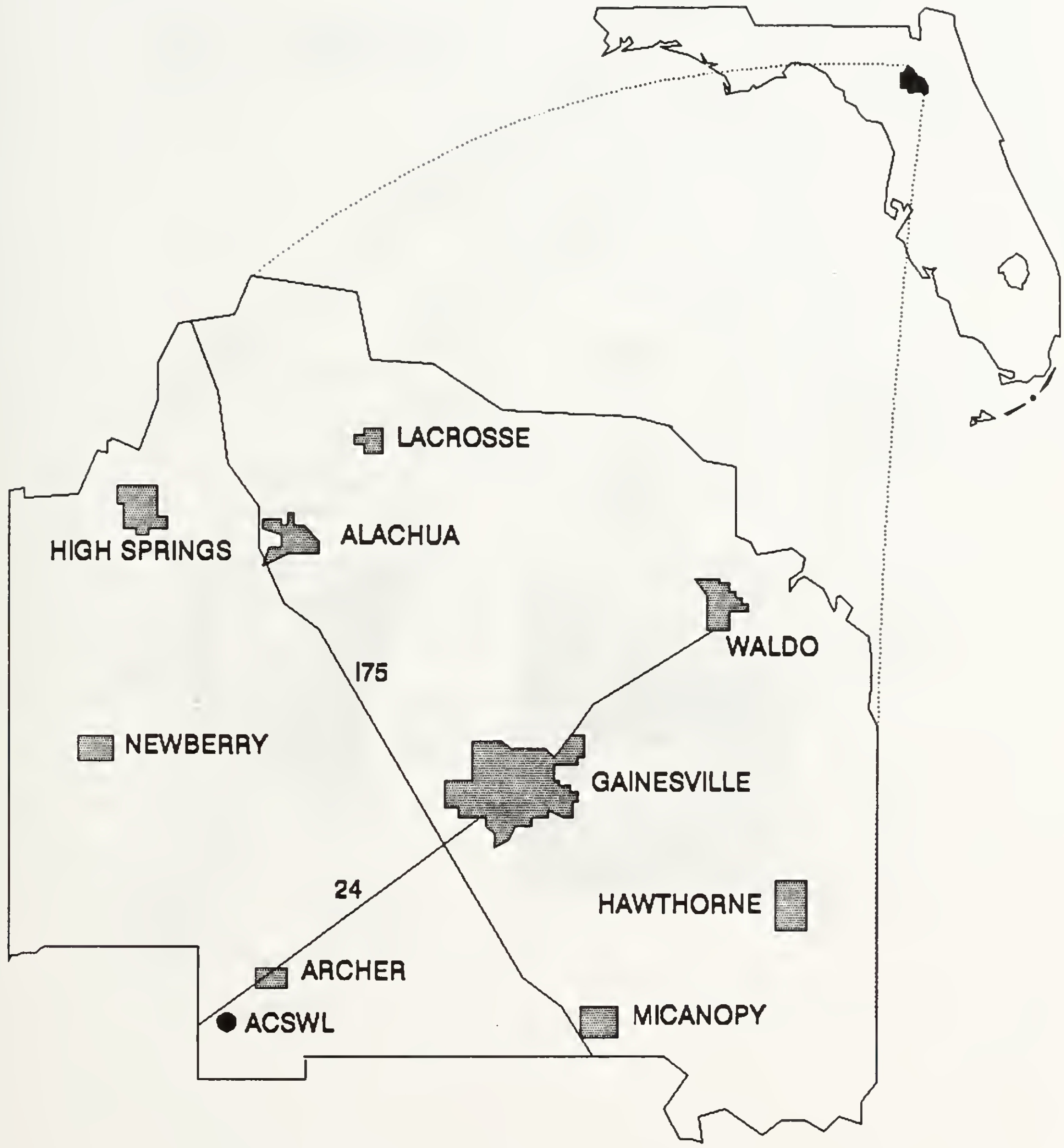



Figure 2-1: Alachua County Southwest Landfill Location Map (Drawing not to scale)

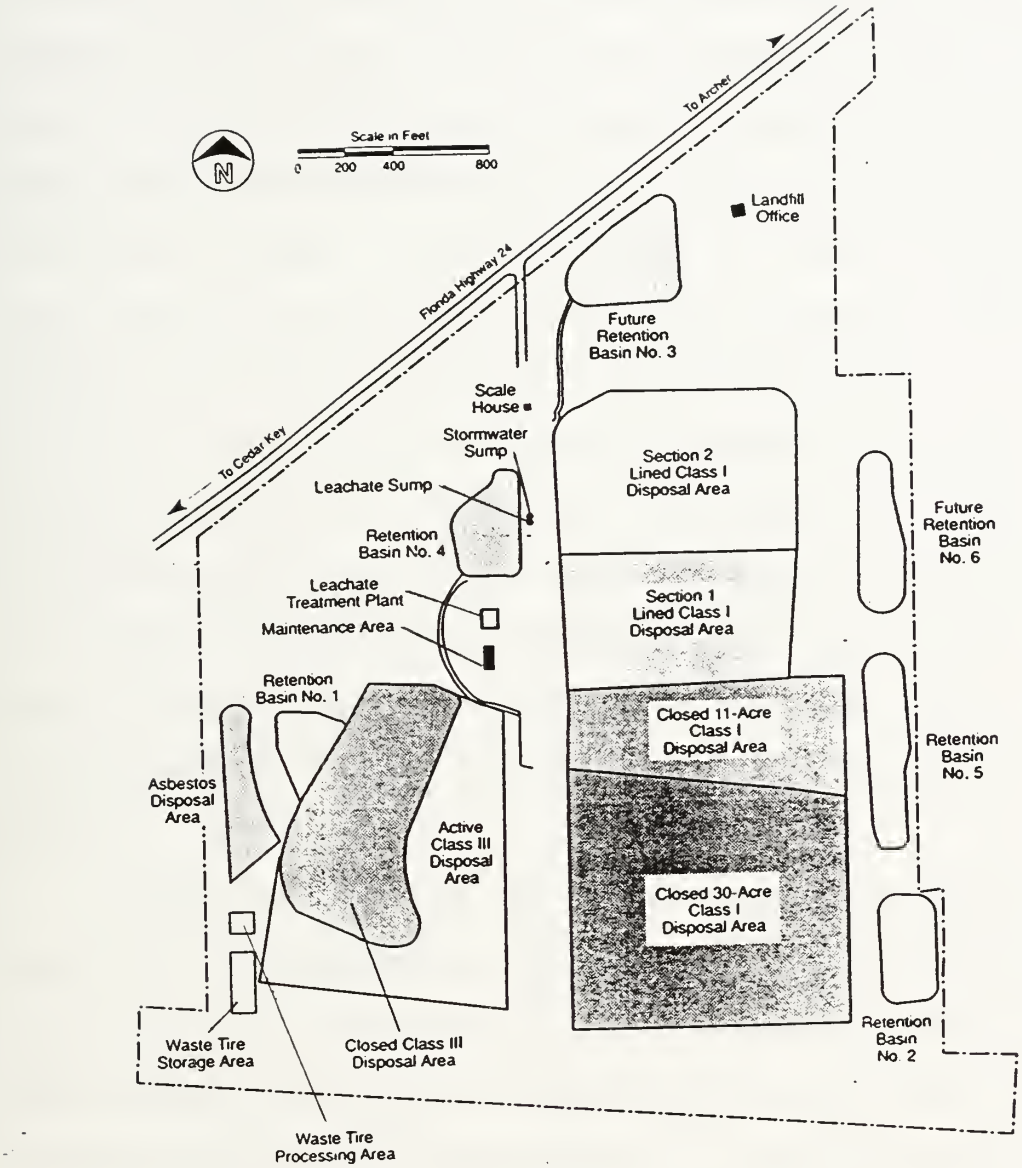



Figure 2-2: ACSWL Site Plan

compacted clay overlain by a 60-mil high density polyethylene (HDPE) plastic liner. The liner is sloped so that leachate, once it reaches the liner, flows by gravity to a series of collection laterals and ultimately out of the landfill into a collection sump. The leachate is then collected in equalization tanks and a portion is pumped back to the landfill for reinfiltration into the solid waste.

The ACSWL is situated on the eastern perimeter of the Brooksville Ridge. The Brooksville Ridge is a north-south oriented area of sand hills that extends from the western area of Alachua County southward to the vicinity of Dade City in Pasco County, approximately 110 miles away. The ridge is approximately 6 miles wide in the area of the landfill (White 1970).

Surface features of the landfill site consist of rolling sand hills and occasional depressions. The general elevation of the site is between 90 and 100 feet above mean sea level. The maximum elevation is approximately 125 feet while the minimum elevation is approximately 70 feet (CH2M-Hill 1986).

The surface soils in the area consist of loose permeable sands which extend below the depth of the landfill. Limestone underlies the site at a depth of approximately 55 to 65 feet. This limestone is the upper surface of the Floridan aquifer and is the principal source of groundwater in the area.

The Floridan Aquifer is divisible into an upper and lower aquifer within the western area of Alachua County (Sproul

1986). The estimated thickness of the upper unit in the vicinity of the landfill is approximately 200 feet. The transmissivity of the aquifer has been determined to be approximately 165,000 gpd/ft (Clark 1964). The groundwater flow in this area of the Floridan is toward the northeast.

# CHAPTER 3

# LITERATURE REVIEW

## GAS PRODUCTION

Measurement and prediction of LFG and methane yields from sanitary landfills is extremely difficult (Barlaz et al. 1989, Barlaz et al. 1990, Pohland 1986). Since no two landfills are alike, the many factors which affect LFG production can vary significantly from one site to another, and even zone-to-zone within a single landfill, making it virtually impossible to use any single type of formula to predict, with a high degree of certainty, the true LFG production rate for a given landfill (Rice 1989, Schumacher 1983). For this reason, many smaller landfills are bypassed for energy recovery projects as a result of uncertain economics (Pohland 1986). Currently, the most widely utilized practice in the estimation of gas flow rates at full-scale landfills is through pump testing (Barlaz 1990). The concept is to pump gas from the site, measuring the volume and composition of the gas, and then to use pressure sensing probes to determine the radius of influence. This process can become quite expensive. Wolfe (1990) gives an estimate of $100,000 or more for a test that

predicts gas volumes to within an assumed ±20%. Wolfe further states that for a site with similar characteristics to one previously tested, a "mini-test" with an assumed accuracy of ±35% would cost approximately $25,000.

Landfill gas is a natural by-product of the decomposition of organic refuse in sanitary landfills. Biodegradable organic components of landfilled solid waste decompose via a combination of biological, chemical, and physical processes (Ham 1979). Methane gas is produced through biological decomposition only, however, interdependencies between the three processes listed above must be considered.

Biological decomposition is the conversion of carbonaceous components into cellular and partially decomposed matter and gaseous end products. Chemical decomposition is the hydrolysis, dissolution-precipitation, sorption-desorption or ion exchange of the wastes' components. This results in greater mobility of the altered refuse constituents as a result of changes in chemical characteristics. Physical decomposition is the breakdown or movement of waste components by the rinsing or flushing action of water movement as a result of pressure gradients. For further description of these processes, see Ham (1979).

Landfill gas generation occurs primarily under two distinct sets of conditions, aerobic and anaerobic.
Figure 3-1 is the pattern assumed to be a typical depiction of the sequence of events during gas production (Farquhar and

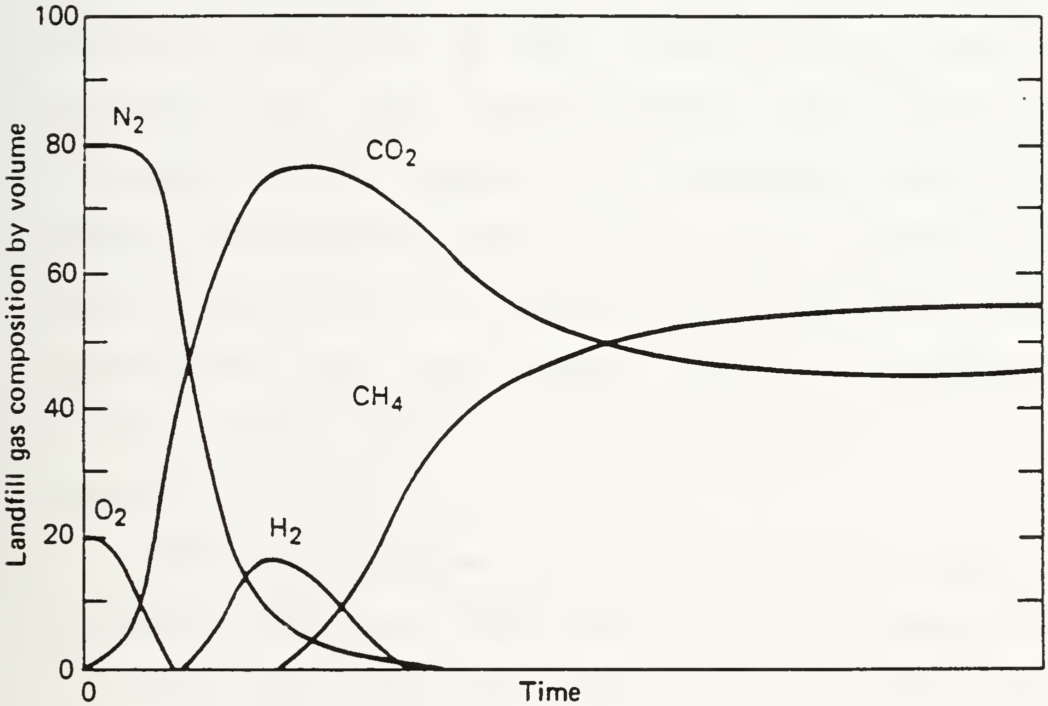



Figure 3-1: Landfill Gas Composition
(Cheremisinoff and Morresi 1976)

Rovers 1973, Cheremisinoff and Morresi 1976, Schumacher 1983). Anaerobic gas production is typified by somewhat lower temperatures (37°C to 54°C), significantly higher methane concentrations (45 to 57%) and lower carbon dioxide concentrations (40 to 48%). Anaerobic gas production will continue until the non-refractory carbonaceous material is degraded or until oxygen is re-introduced into the refuse, at which time decomposition would return to aerobic conditions. This shift in the presence of oxygen would not stop LFG production, but would merely retard it temporarily (Rice 1989). This pattern can be broken down to four distinct phases.

The first phase, the transformation from aerobic to anaerobic activity, begins soon after the refuse is placed in a landfill and continues until all of the entrained oxygen is depleted from the voids within the refuse and the organic material itself. Volatile fatty acids begin to appear in the leachate. Carbon dioxide is produced in approximate molar equivalents to the $O_2$ consumed. The gas produced is characterized by relatively high temperatures (54°C to 71°C), high carbon dioxide content and low methane content. Aerobic decomposition may occur in the bottom lifts of a landfill for as little as six months to as long as 18 months. In the upper lifts, however, decomposition may take as little as three to six months as methane- and carbon dioxide-rich gas from below

is able to more rapidly flush out the oxygen from the voids in the upper sections (Rice 1989).

Upon depletion of $O_2$, the gas production pattern enters the second phase where anaerobic activity is dominant. During this phase there is a significant increase in $CO_2$ production and production of some $H_2$. Although some $N_2$ production via denitrification may exist, overall there is a large displacement of $N_2$. There is not yet a significant production of $CH_4$. Volatile fatty acid formation becomes dominant and the pH drops (Miller et al. 1991a).

The third phase is often considered the unsteady phase. This is where the concentration of $CH_4$ increases to a relatively constant terminal value. Volatile fatty acids are converted to methane and carbon dioxide. Since some of the methanogenic bacteria are capable of using $H_2$ at a very rapid rate, hydrogen is removed in the initial portion of this phase.

The fourth and final phase is characterized by steady production rates of the gases. This does not preclude changes in gas production resulting from changes in environmental conditions or nutrient depletion.

Pohland (1986) describes two additional phases for consideration: the initial adjustment phase and the final maturation phase. The initial adjustment phase occurs at the time the waste is initially placed in the landfill just prior to the first phase described above. Moisture accumulation and

initial subsidence occurs. The final maturation phase follows the previously defined fourth phase. Biological activity and gas production essentially stops. There is a slow restoration to natural conditions and the landfill very slowly returns to an aerobic state.

It will be established later in this section that the many factors that affect LFG production vary greatly. It can therefore be anticipated that the composition of LFG will also differ. Landfill gases are typically 40 to 60% methane with the remaining volume composed primarily of carbon dioxide and 1 or 2% (total) of other miscellaneous inorganic gases and organic vapors (Pohland 1986). Analysis of the ACSWL gas was performed by Dwyer (1992). The ranges of Dwyer's findings are presented in Table 3-1. Table 3-2 is a "typical" breakdown of LFG by component as cited by Ham et al. (1979).

## FACTORS THAT AFFECT GAS PRODUCTION DURING METHANE FORMATION

The total volume of gas generated over the entire life of a landfill is a direct function of the total volume of organic waste contained in the landfill, although the rates of decomposition will vary: some rapidly, some moderately, and some over a much longer period of time (Rice 1989). The incremental rate at which the gas is produced is primarily a function of the type of wastes involved, e.g., food waste versus paper or cardboard, but the overall rate for all refuse

| Compound | Active Section Low | Active Section High | Active Section Ave | 11-acre Section Low | 11-acre Section High | 11-acre Section Ave | 30-acre Section Low | 30-acre Section High | 30-acre Section Ave |
|---|---|---|---|---|---|---|---|---|---|
| $CO_2$ | 55.9 | 56.2 | 56.05 ±0.15 | 42.8 | 57.6 | 54.2 ±5.7 | 53.5 | 65.7 | 30.5 ±2.6 |
| $CO_2$ | 39.9 | 41.7 | 40.8 ±0.9 | 42.8 | 45.3 | 44.3 ±0.7 | 33.9 | 44.7 | 39.5 ±2.6 |
| $O_2$ | 0.0 | 0.3 | 0.15 ±0.15 | 0.0 | 0.8 | 0.1 ±0.2 | 0.0 | 9.7 | 0.8 ±1.8 |
| $N_2$ | 0.0 | 1.6 | 0.8 ±0.8 | 0.0 | 0.8 | 0.01 ±0.2 | 0.0 | 2.1 | 0.2 ±0.5 |

Table 3-1 : Percent Composition of ACSWL Gas (Dwyer 1992)

| Component | Component percent (dry volume basis) |
|---|---|
| Methane | 47.5 |
| Carbon dioxide | 47.0 |
| Nitrogen | 3.7 |
| Oxygen | 0.8 |
| Paraffin hydrocarbons | 0.1 |
| Aromatic & cyclic hydrocarbons | 0.2 |
| Hydrogen | 0.1 |
| Hydrogen sulfide | 0.01 |
| Carbon monoxide | 0.1 |
| Trace compounds[1] | 0.5 |
| **Characteristic** | **Value** |
| Temperature (at source) | 106°F (41.1°C) |
| High heating value (hhv)[2] | 476 Btu/scf |
| Specific gravity | 1.04 |
| Moisture content | Saturated (trace compounds in moisture)[3] |

1 Trace compounds include sulfur dioxide, benzene, toluene, methylene chloride, perchlorethylene, and carbonyl sulfide in concentrations up to 50 ppm.

2 Landfill gas (as received) from Palos Verde landfill has a hhv of 581 to 586 Btu/scf (Bowerman 1977). Landfill gas (as received) from a Mountain View landfill test well has a hhv of 441 to 451 Btu/scf with a 20-21 percent nitrogen content by volume (Blanchet 1977, Carlson 1977).

3 Trace compounds include organic acids 7,06 x $10^{-3}$ ppm and ammonia 7.1 x $10^{-4}$ ppm.

TABLE 3-2: Typical Landfill Gas Composition and Characteristics (Ham et al. 1979)

components in a given section of a landfill is also influenced by a variety of other factors such as moisture, particle size, pH, composition, nutrient addition, depth, temperature, and gas extraction rates (Barlaz et al. 1990, Ham et al. 1979, Farquhar and Rovers 1973, Pohland 1986, Rice 1989). Some of these parameters and how they affect methane production will be briefly discussed in this section in order to better understand the dynamics of landfill gas production over time.

Moisture content. Moisture content has been described as one of the most important factors in LFG production and landfill stabilization (Chian and Dewalle 1979, Farquhar and Rovers 1973, Ham et al. 1979, Pohland 1986). There have been many studies of the impacts of moisture content with variable findings. Tchobanoglous et al. (1970) gives a range of typical moisture contents at time of disposal to be between 15 and 40%. Laquidara (1986) approximates the average moisture content in fresh MSW to be 25%.

For gas production, Chian and DeWalle (1979) reported an optimum moisture content for landfills between 43 and 50% while Ham (1979) stated that a minimum of 50% moisture content is needed to enhance gas generation. Pohland (1986) has more recently found that MSW stabilization rates increase with moisture content up to 60%, after which stabilization rates remain constant, neither increasing nor decreasing. Farquhar and Rovers (1973), however, site Ramaswamy (1970) and Songonuga (1970) as finding that gas production rates

increased with increased refuse moisture content with a maximum production rate occurring at moisture contents from 60 to 80% wet weight. EMCON Associates (1980) provide evidence that the production rate of a gas may continue to increase with the "increasing moisture content values in excess of the field capacity of the landfill."

The percentage of $CH_4$ in the gases also increased with the increased moisture content (Barlaz et al. 1990). The flow of moisture through a landfill may be expected to stimulate microbial activity by providing better contact between substrates, soluble nutrients, and micro-organisms.

Particle size. There exists a controversy with regard to refuse particle size and its affect on decomposition rates and LFG production. For example, Buivid et al. (1981) and DeWalle et al. (1978) suggest that a larger sized particles (25 to 35 cm) stimulate methane production relative to particle sizes of 2.5 to 15 cm, where Ham (1982) concluded that shredded refuse (7.5 cm and below) stimulated methane production. Barlaz et al. (1990) and Pohland (1986) reported that studies are inconclusive and often contradictory. It would appear that a well-mixed, shredded waste stream permits greater contact between the constituents required for methane production: moisture, substrate, and microorganisms. Thus, a smaller particle size could result in an increase in hydrolysis, however, a rapid increase in hydrolysis may then lead to a build-up of acidic end products and a lower pH

(Barlaz 1990) resulting in a potential for lower gas production.

pH. pH has been found to be a very important and reliable predictor of methane generation rates in MSW. It is generally accepted that the optimum pH for methanogenic bacteria is between 6.4 and 7.4 (Barlaz 1990, Pohland 1986, Schumacher 1983). Deviations from this range may result in reduced gas production (Farquhar and Rovers 1973). Rhyne and James (1978), as cited by Schumacher (1983), report that the average pH of a landfill does not drop below 6.2 when methane is being produced.

Depth. Oxygen is toxic to methanogenic bacteria. The presence of small quantities of oxygen will inhibit the growth of methanogenic bacteria, thus slowing the production of methane gas (Schumacher 1983). For this reason the depth of the landfill becomes an important factor. In a deep landfill the oxygen in the infiltrating air is consumed in the upper portions of the landfill and does not hinder the anaerobic process in the lower portions.

Nutrients. All life forms require a source of nutrients. Various nutrients are required for the growth of bacteria in the landfill. Primarily carbon, hydrogen, nitrogen, and phosphorus must be present in sufficient quantities. Small amounts of sodium, potassium, sulfur, calcium and magnesium are also needed (EMCON Associates 1980).

Temperature. Optimum temperatures for gas production are in the range from 30°C to 35° C. Temperature effects on methane production are generally described in the context of three temperature ranges: thermophilic, mesophilic, and psychrophilic. The thermophilic range is characterized by temperatures greater than 44°C, the mesophilic range with temperatures between 20 and 44°C, and the psychrophilic range with temperatures less than 20°C (Farquhar and Rovers 1973). The general trend is for increased gas production up to an optimal temperature of about 55°C beyond which decomposition rates will be reduced dramatically. Methane production is sensitive to abrupt changes in temperature and may be disturbed by changes as small as 1 to 2°C (Farquhar and Rovers 1973).

Refuse Composition. It is important to understand the composition of MSW prior to reviewing studies of refuse decomposition and LFG generation. Refuse high in organic matter such as food wastes will decompose rapidly, garden trimmings and paper decompose at a moderate rate, whereas inorganic materials such as demolition and construction debris will be relatively unaffected by the biological decomposition process. Special wastes mixed with the refuse can have important effects upon gas generation. While sewage sludge mixed with the refuse can enhance gas generation, certain industrial wastes can inhibit methane production (Schumacher 1983).

Visual categorization (categorizations made during hand sorting for composite studies) such as glass, paper, metals, etc., has traditionally been the method to classify MSW. A typical composition profile is shown in Figure 3-2. It should be recognized that the composition represented in Figure 3-2 is subject to wide variability dependent upon such factors as time of year, geographic location, population affluence, etc. A composition study of the ACSWL was performed on the active section in 1991 (TIA, 1991). The results of the study are presented in Table 3-3.

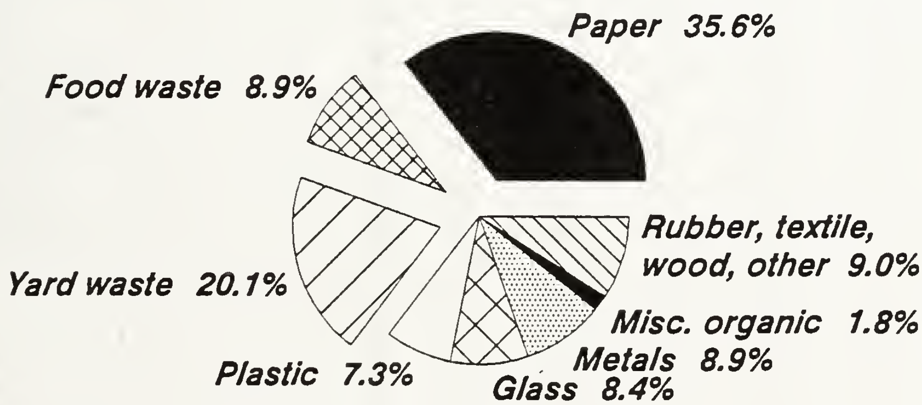
Barlaz (1990) states that recently published data on the chemical composition of refuse have been used to calculate methane potential for each chemical constituent. However, Barlaz further states that the few data that are available for methane yields from full-scale landfills indicate that actual yields are between 1 and 50% of those calculated from refuse biodegradability data and stoichiometry (Barlaz et al. 1989, Barlaz et al. 1990). Stoichiometric calculations will be presented and discussed in more detail below.

STOICHIOMETRIC ESTIMATION OF LFG PRODUCTION

The volume of gas produced during anaerobic decomposition of refuse in a landfill may be estimated in several ways. Ham (1979) gives a generalized equation describing gas generation by the methane formers (in concert with various associated

# Typical Solid Waste Composition

## (Franklin Assoc., 1988)




*Note: Paper, yard waste, and food waste represent the organic fraction of the waste that is readily degradable.*

*Figure 3-2*

| Material | Total Waste Landfilled | | | Class 1 Landfill Waste |
|---|---|---|---|---|
| | Alachua County | Gilchrist County | Weighted Average | |
| Newsprint | 6.8 | 6.7 | 6.8 | 8.6 |
| Corrugated Paper | 11.1 | 9.4 | 11.1 | 14.1 |
| High Grade Paper | 2.9 | 1.7 | 2.9 | 3.7 |
| Mixed Scrap Paper | 8.2 | 3.4 | 8.1 | 10.3 |
| Non-Recyclable Paper | 8.5 | 16.0 | 8.7 | 11.0 |
| Plastic (PET)- | 0.3 | 0.4 | 0.3 | 0.4 |
| Plastic (HDPE)- | 1.0 | 0.6 | 1.0 | 1.3 |
| Other Plastic Containers | 0.6 | 1.1 | 0.6 | 0.8 |
| Film Plastic - | 4.4 | 5.0 | 4.4 | 5.6 |
| Other Plastic | 3.9 | 4.5 | 3.9 | 4.9 |
| Glass-Other | 0.0 | 0.0 | 0.0 | 0.0 |
| Clear Glass Containers | 2.2 | 4.2 | 2.2 | 2.8 |
| Color Glass Containers | 1.1 | 1.4 | 1.1 | 1.4 |
| Aluminum Cans | 0.9 | 1.0 | 0.9 | 1.1 |
| Tin/Steel Cans | 1.5 | 3.1 | 1.5 | 1.9 |
| Ferrous Metals | 0.9 | 2.3 | 0.9 | 1.1 |
| Non-Ferrous Metals | 0.6 | 0.3 | 0.6 | 0.8 |
| Rubber | 0.6 | 0.9 | 0.6 | 0.8 |
| Textiles | 3.2 | 2.3 | 3.2 | 4.1 |
| Leather | 0.0 | 0.1 | 0.0 | 0.0 |
| Food Waste | 4.5 | 3.6 | 4.5 | 5.7 |
| Yard Waste | 4.4 | 2.9 | 4.4 | - |
| Mixed Materials | 2.7 | 2.9 | 2.7 | 3.4 |
| C & D Debris | 19.9 | 16.7 | 19.8 | - |
| Ceramics | 0.5 | 0.1 | 0.5 | 0.6 |
| Miscellaneous | 6.1 | 4.5 | 6.1 | 7.7 |
| H. Hazardous Waste | 1.0 | 1.0 | 1.0 | 1.3 |
| Diapers | 2.1 | 3.9 | 2.1 | 2.7 |

Table 3-3: Landfill Composition (TIA 1991)

(The above values are expressed as percentages.)

micro-organisms such as the fermentors and acetogenic bacteria) for a substrate of overall composition $C_aH_bO_cN_dS_e$ as:

$$C_aH_bO_cN_dS_e+\left(\frac{4a-b-2c+3d+e}{4}\right)H_2O\rightarrow\left(\frac{4a+b-2c-3d-e}{8}\right)CH_4$$

$$+\left(\frac{4a-b+2c+3d+2e}{8}\right)CO_2+dNH_3+eH_2S \qquad (1)$$

Tchobanoglous et al. (1977) and Barlaz (1990) describe a somewhat modified equation, one without the sulfur constituent, as:

$$C_aH_bO_cN_d+\left(\frac{4a-b-2c+3d}{4}\right)H_2O\rightarrow\left(\frac{4a+b-2c-3d}{8}\right)CH_4$$

$$+\left(\frac{4a-b+2c+3d}{8}\right)CO_2+dNH_3 \qquad (2)$$

where C, H, O, N, and S represent carbon, hydrogen, oxygen,nitrogen, and sulfur, respectively. Tchobanoglous et al. (1977) determined, on a wet-weight basis, the theoretical standard cubic feet (scf) of gas generated per pound of refuse to be 3.2 for $CO_2$ and 3.3 for $CH_4$. Pacey (1976) estimates the actual production of methane per pound of refuse to be in the range of 1 to 3 scf. Because of different approaches and assumptions, the gas yields per pound of wet refuse range from 3.0 to 8.0 scf for total LFG and from 1.5 to 4.3 scf for methane (Schumacher, 1983).

Miller et al. (1991a) reports an average elemental composition for the lined landfill cell as $CH_{1.682}O_{0.955}N_{0.011}P_{0.027}$. When the value of nitrogen is set to 1, the approximate formula for the solid wastes becomes $C_{91}H_{153}O_{87}NP_{0.027}$. Given the composition of the Class I landfill from Table 3-1 and the assumptions as listed below, the estimated total amount of gas that will be produced from the ACSWL can be calculated using equation (2) as follows (Tchobanoglous et al. 1977):

1. From Table 3.3, the total weight of biodegradable organic material in 100 lb of solid waste is equal to 53.4 lb., calculated by the summation of the paper and food wastes from the Class 1 Landfill Waste column. Assuming that the initial moisture content is 25 percent (Laquidara, 1986) and is associated with the organic components, and that the total organic material is available for decomposition, the organic material (dry basis) is:

$$\text{lb, organic material (dry basis)} = 53.4\text{ lb} - (53.4\text{ lb})(0.25) = 40.05\text{ lb}$$

2. Inserting the values from Miller et al. (1991), equation (2) can be rewritten as:

$$C_{91}H_{153}O_{87}N + 10H_2O \rightarrow 42.5CH_4 + 48.5CO_2 + NH_3$$

Multiplying by the respective molecular weights gives:

$$\underset{C_{91}H_{153}O_{87}N}{(2651)} + \underset{H_2O}{(180)} \rightarrow \underset{CH_4}{(682.5)} + \underset{CO_2}{(2134)} + \underset{NH_3}{(17)}$$

3. The weight of methane and carbon dioxide generated is then determined as:

$$\text{Methane} = (682.5 / 2651) \times (40.05 \text{ lb}) = 10.31 \text{ lb}$$

$$\text{Carbon dioxide} = (2134 / 2651) \times (40.05 \text{ lb}) = 32.24 \text{ lb}$$

4. Converting the weight of the gases to volume, assuming that the densities of methane and carbon dioxide at 0°C and 1 atm are 0.0448 and 0.1235 lb/ft$^3$ (Schumacher 1983), respectively:

$$\text{Methane} = (10.31 \text{ lb})/(0.0448 \text{ lb/ft}^3) = 230.13 \text{ ft}^3$$
$$\text{Carbon dioxide} = (32.24 \text{ lb})/(0.1235 \text{ lb/ft}^3) = 261.05 \text{ ft}^3$$

5. The total theoretical amount of gas generated per unit weight would be:

Based on dry weight of organic material-
$$(230.13 + 261.05 \text{ ft}^3)/(40.05 \text{ lb}) = 12.26 \text{ ft}^3/\text{lb}$$

Based on 100 lb of solid waste-
$$(230.13 + 261.05 \text{ ft}^3)/(100 \text{ lb}) = 4.91 \text{ ft}^3/\text{lb}$$

6. The percentage of the resulting gas is:

$$\text{Methane: } 230.13 \text{ ft}^3 / 491.18 \text{ ft}^3 = 46.9\ \%$$

$$\text{Carbon dioxide: } 261.05 \text{ ft}^3 / 491.18 \text{ ft}^3 = 53.1\ \%$$

As cited by Ham et al. (1979) and Pohland (1986), however, the above method of estimation oversimplifies the complex process of solid waste decomposition. There is a general failure to include the influences of a number of factors such as the degree of decomposition, nutrient availability, physical-chemical interactions, and biological

inhibitions which all will generally serve to decrease the methane yields (Pohland 1986). The actual amount of recoverable gas would, therefore, be considerably less than the computed theoretical values. As previously cited, Barlaz et al. (1989, 1990) reported that from the few data that are available on methane yields from full-scale landfills indicate that methane yields are between 1 and 50% of the totals calculated from stoichiometry. Under optimum conditions, it is estimated that 30 to 70 percent of the computed amount of gas generated per unit weight could be achieved within two years and up to 70 percent within 5 years (Tchobanoglous et al. 1977).

The above equations assume that all organics will be decomposed, but lignin, for example, is not degradable to any practical extent under anaerobic conditions (Barlaz 1990, Ham 1979, Pohland 1988). Calculations of gas production should utilize the biodegradable fraction (BVS) of the TVS only. The equations also assume that all degradation occurs anaerobically and all organic matter is decomposed to either methane or carbon dioxide. It would then follow that any matter leaving the landfill, as a gas or a component of leachate, would not contain any organic matter except for methane, which is not the case. Ham (1979) states that further assumptions are made that all refuse components are available to the organisms simultaneously so that a balance of substrates and nutrients are ever present. This is not the

case because components such as food wastes with high sugar, fat, and starch contents are more readily degradable than components such as paper, garden wastes, wood and natural fiber textiles which contain cellulose. Furthermore, a portion of the degraded matter will be utilized for bacterial cell synthesis, which is also not included in the generalized equations.

In addition to the above equation inaccuracies, there is the likelihood that the composition of the gas produced and measured at the landfill will not be as calculated because of the much higher solubility of carbon dioxide in water than methane. This consideration alone suggests that the greater the water availability and moisture content of the refuse, the higher the methane concentration will be in the gas even though the amount of gas generated per volume of refuse remains unchanged.

## MODELS FOR PROJECTION OF LANDFILL GAS PRODUCTION

The wide range in types of decomposable matter present in solid waste suggests that no simple equation or rate constant adequately describes the rate of decomposition or the rate of methane generation within a landfill (Ham 1977). Schumacher (1983) and Barlaz et al. (1989, 1990) stated that there is no available field data from sanitary landfills to allow verification of kinetic models to describe the time dependency of gas production in sanitary landfills. It is of interest to

note that energy recovery projects are often rejected because of the unpredictability of methane yields and production times (Barlaz 1989, Wolfe 1990). Pohland (1986) stated that field observations serve as the best indicators of gas yields in sanitary landfills, as laboratory analysis is often misleading; lysimeters generally have a higher gas yield per unit volume than actual landfills or larger landfill simulators partly as a result of controlled conditions for the lysimeters and gas losses through landfill cover.

Theoretical Models. There is little evidence, as cited by Ham et al. (1979), that organic decomposition in sanitary landfills proceed according to any standard order of kinetic expression. Theoretical approaches to the estimation of the rate of gas generation in a landfill, however, generally involve the development of models based on the following equations (Barlaz et al. 1990, Ham et al. 1976, Schumacher 1983):

$$-\frac{dc}{dt}=k \tag{3}$$

or

$$-\frac{dc}{dt}=kc \tag{4}$$

where c = concentration of decomposable matter remaining at time t and k = reaction rate constant.

Equation (3) describes a zero order reaction in which the reaction rate is independent of the concentration of organic

matter remaining to be decomposed (Ham et al. 1979). Equation (4) is the first order reaction rate and is the most commonly utilized (Ham et al. 1979, Barlaz et al. 1990). Equation (4) states that the rate of loss of decomposable matter is proportional to the amount of decomposable matter remaining (Ham and Barlaz 1989). In a landfill, however, many other factors may influence the gas generation rate such as moisture, nutrients, or inhibitory compounds (Barlaz et al. 1990).

Findikakis et al. (1988) presented data to suggest that the first-order model was not accurate in the prediction of methane production. Barlaz et al. (1990) propose that a zero-order kinetic model seems to most accurately describe the rate of gas production at a full-scale landfill during the most active periods of gas generation. Many of these full-scale landfills where gas is recovered produce approximately the same volume of gas on an annual basis over the active gas generation period.

Lu and Kunz (1981) as cited by Schumacher (1983) developed a model to predict methane production based on field measurements of changes in landfill gas pressure caused by pumping gas from the landfill. Measurement of the LFG pressure taken at three points outward radially from an extraction well are required for the model.

Schumacher (1983) cites several modeling techniques and states that there is no available field data for verification

of the kinetic models for the description of time dependency of gas production. Many assumptions must be made for the models described by Schumacher such as decomposition half-lives, categorization of wastes based upon decomposition rates, previous volumes of gas produced, volume of gas remaining to be produced based upon stoichiometric calculations, and the time at which maximum gas production will occur.

The Scholl Canyon kinetic model, as described by Schumacher (1983), is a model of substrate-limited microbial growth that can be described by equation (4). This model is analogous to models often used to describe oxygen uptake in aqueous solutions by bacteria. One example of such an application is the reduction of biochemical oxygen demand (BOD) in a BOD bottle.

Laquidara et al. (1986) developed a model for prediction of methane production in landfills that no longer receive refuse. The methane production is projected from the first-order model using total volatile solids (TVS) as the substrate concentration. TVS refers to the organic fraction of the sum of the inorganic and organic compounds known as total solids (TS). TVS are categorized as easy, moderate, or hard to degrade, and decay coefficients are assigned to each fraction. There was no suggestion of the procedure for independent measurement of these decay coefficients. At landfills where the model does not fit the predicted methane generation, it

was, however, suggested that the model could be calibrated to field data by adjusting the decay coefficients. This particular model requires multiple borings and analysis for total solids, total volatile solids, total organic carbon, and lignin (Laquidara et al. 1986).

Findikakis and Leckie (1979) also developed a model for gas production. This model estimated gas losses through the surficial layer of the landfill and predicted pressure gradients. Refuse decomposition rates, half-lives, and a physical description of the landfill were all required as input. Barlaz et al. (1990) cites that Findikakis later modified this model to describe the biological reactions involved.

Barlaz (1990) summarizes that dynamic field testing with a limited number of wells does not provide accurate production estimates, either for sections of a landfill or for an entire landfill site. Information gathered from any given well or cluster of wells is valid only for that localized area and cannot be extrapolated over the entire site. Because of the variations in composition, compaction, moisture content, and other factors, the conditions which enhance LFG production rates also vary from section to section.

Predicting LFG production rates through the use of computer or arithmetic models has a great deal of appeal, in part because many people still believe that computer programs can accomplish anything. In practice, however, computerized

LFG production models primarily rely on an assumed standardization of production factors under laboratory conditions instead of considering and evaluating field factors individually. One of the fundamental problems with LFG models, as discussed by Barlaz et al. (1990) and Rice (1989), is the fact that few if any of them have ever been validated through the comparison of their predicted production rates with actual production during the life of a landfill.

Schumacher (1983) states that although the importance of many physical and chemical variables is known in the process of anaerobic decomposition, it is not possible to describe with any certainty the actual conditions within a landfill system. No explicit functional relationships exist among many of the factors that affect microbial activity, such as moisture content, and the kinetic expressions for anaerobic gas production. The approach most often taken is to use the simplified models available and to empirically adjust the kinetic rate constants to account for the variabilities. To better improve LFG generation predictions, further research and field testing is needed to develop models which account for factors such as moisture content, temperature, composition, and density.

# CHAPTER 4

# MATERIALS AND METHODS

## EQUIPMENT AND MATERIALS

There is an unfortunate absence of uniform and reliable data collection protocols for the measurement of landfill gas production and flow (Pohland 1986). The methods, materials, and instrumentation described within this section were designed to be simple and easily reproducible.

Gas Supply. Gas flow was measured from 56 gas vents. The location of each gas vent is shown in Figure 4-1. Typical details of the gas vents are shown in Figures 4-2 and 4-3. Gas was collected from the landfill and channeled through the instrumentation. The vents were constructed using either 4 inch non-perforated or 6 inch perforated PVC pipe for the capped and uncapped sections, respectively. The capped vents were permanently installed by contractor and required no further preparations.

For the uncapped section, a 2 foot diameter casing surrounds the upper 20 feet of each vent riser. As the height of the refuse placed increased, the casing was raised and another section of perforated PVC pipe was connected to extend

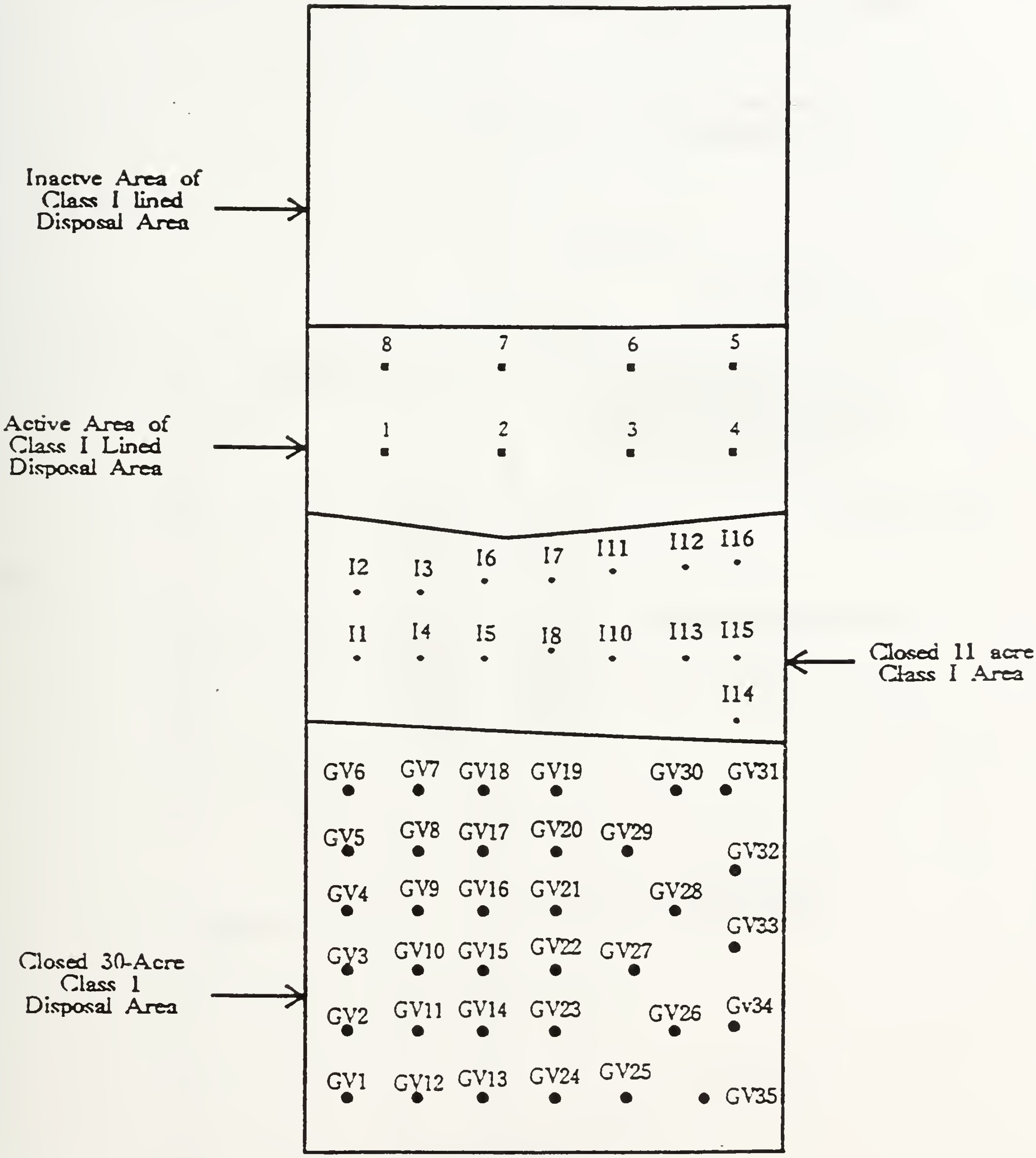



Figure 4-1: ACSWL Gas Vent Identification and Location

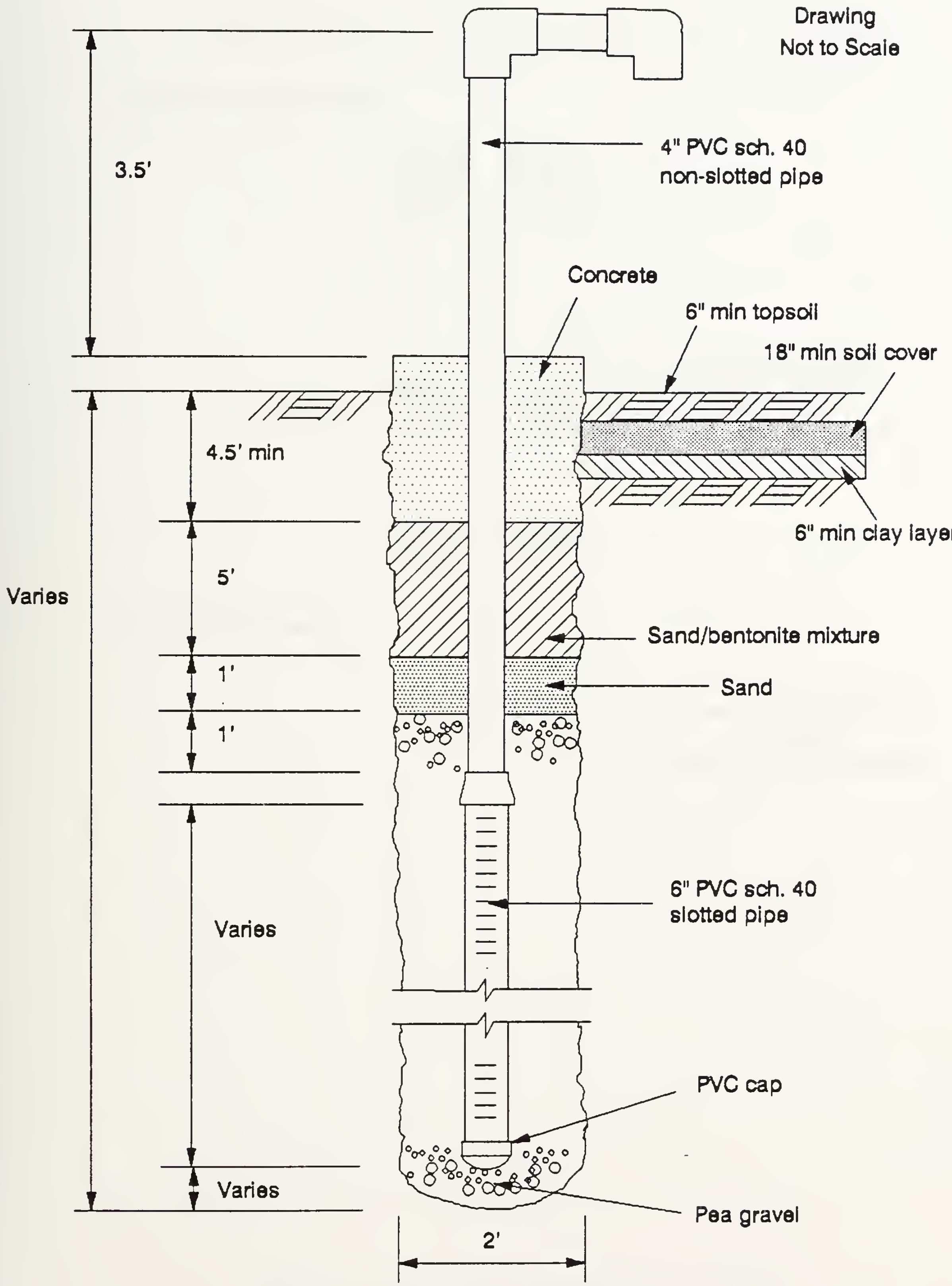



Figure 4-2: Typical vent detail for unlined sections

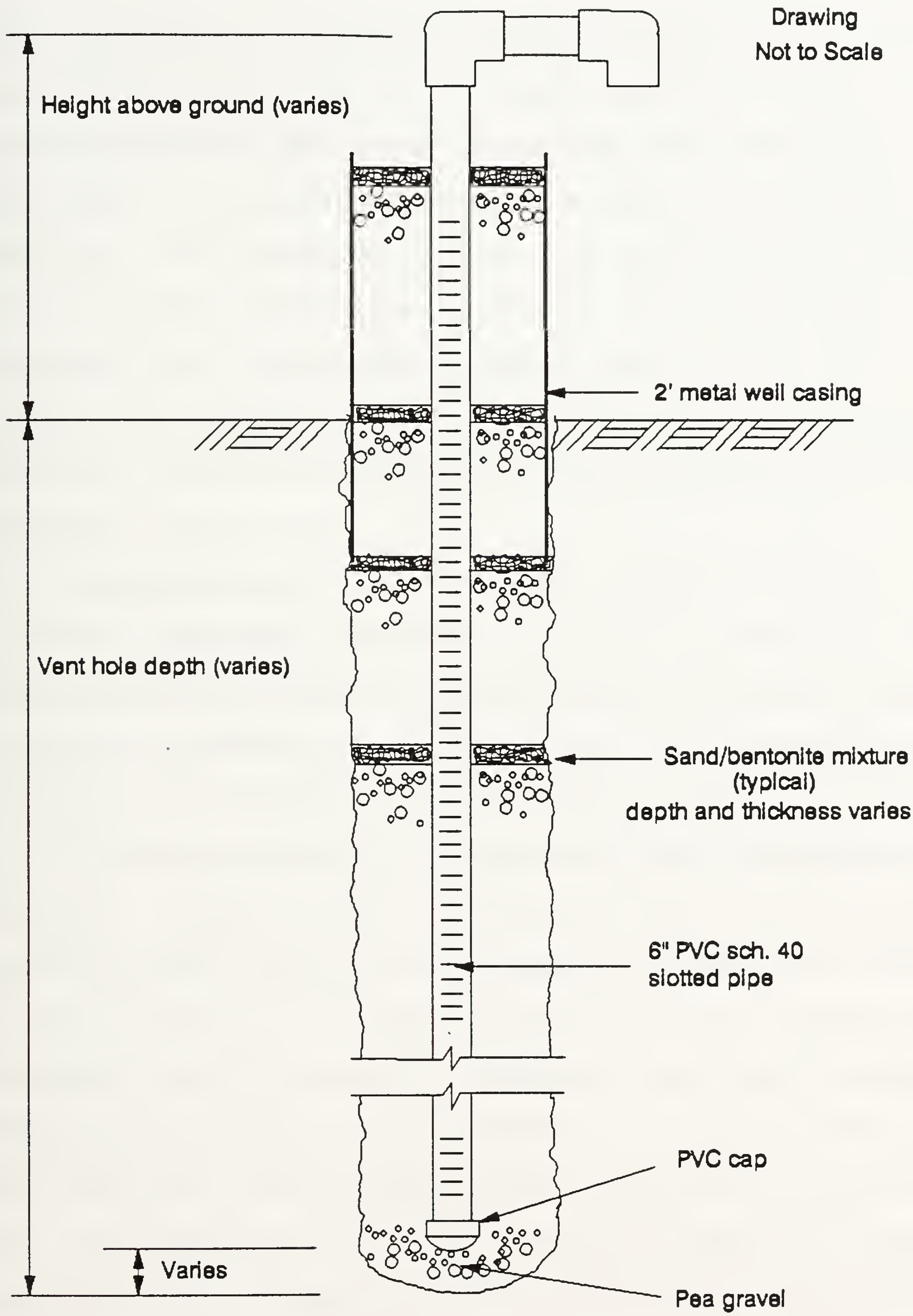



Figure 4-3: Typical vent detail for lined section

the vent upward. Gravel was placed between the PVC pipe and the casing after each lift. Approximately 8 inches of a Barroid Quik-Gel® (bentonite) and sand mixture was placed over the gravel to minimize the escape of gas through the porous material. The bentonite, in turn, was covered with a plastic film to prevent desiccation. The slots in the vent riser that extended above the bentonite barrier were blocked with duct tape. Approximately 6 to 8 inches of sand was then placed above the film and around the tape to prevent any break in the integrity of the seal.

Instrumentation. Measurements of gas flow were taken using the equipment arrangement shown in Figure 4-4. Flow measurements were taken in liters per minute (l/min) utilizing a Gilmont rotameter with a ball float. The rotameter had a scale of 0 to 80 l/min graduated in increments of 5 l/min.

To measure the flow, the diameter of the system had to be reduced. Either a 4 or 6 inch to 1-1/2 inch reducer, depending upon the gas vent diameter, was placed over the end of the gas vent. An 18 inch length of a 1-1/2 inch PVC pipe extension with a centrally located ball valve was installed immediately downstream of the reducer. A 1/8 inch hose barb was tapped into the PVC pipe extension between the ball valve and the reducer and was the location of the gas pressure readings. Downstream of the ball valve the system diameter was further reduced to 1/4 inch, the size of the rotameter intake, through a series of PVC fittings and tygon tubing.

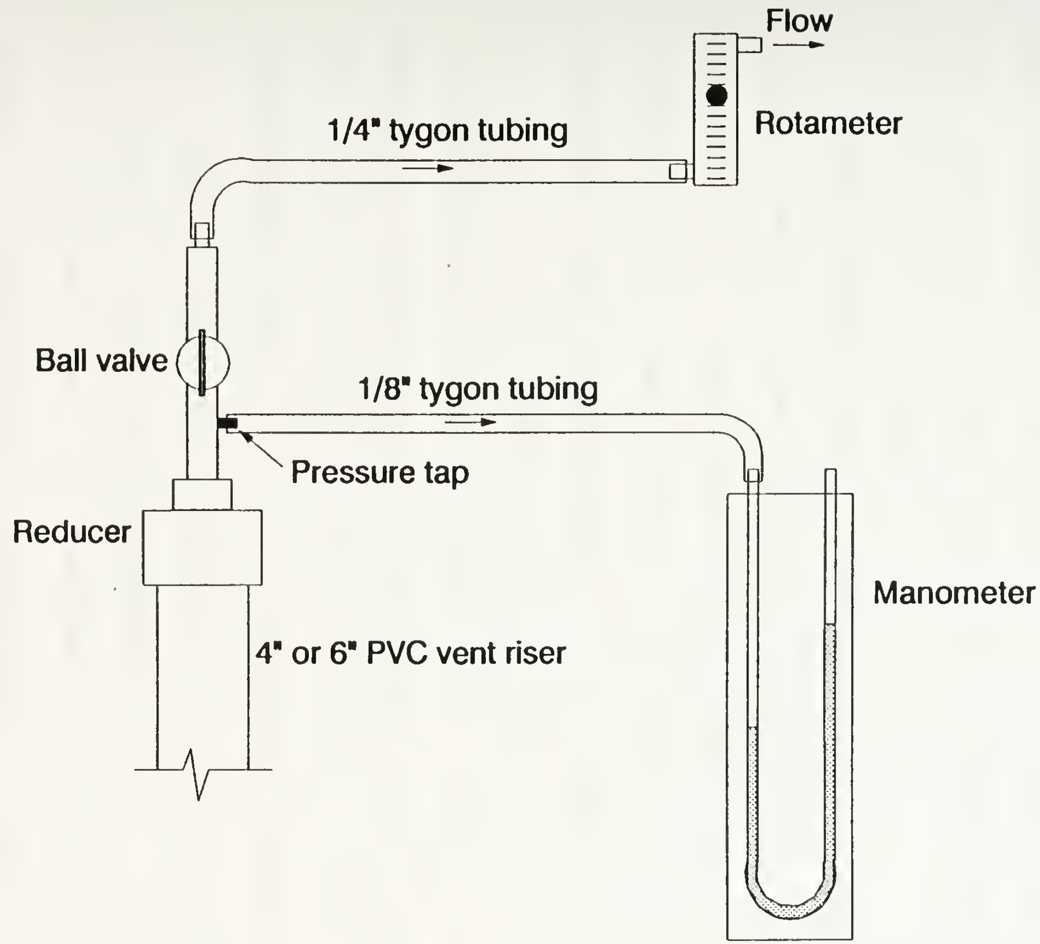



Figure 4-4: Typical Equipment Set-up
(Drawing not to scale)

Gas pressure readings were taken with a water manometer constructed of thin glass tubes and connected by plastic tubing to form a U-tube. Readings were taken by measuring the displacement of the water within the tubes using a measuring tape graduated to 1/10 inches. The U-tubes and measuring tape were mounted on a wood frame with a clear plastic face plate for protection and ease of transport.

For accuracy, the rotameter was calibrated utilizing an orifice meter. The equipment arrangement utilized in the calibration of the rotameters is shown in Figure 4-5. The orifice meter was placed immediately downstream of the rotameter when measurements were taken for calibration purposes. The design of the orifice meter used in the calibration is shown in Figure 4-6. The body of the orifice meter was constructed of a threaded 1-1/4 inch inside diameter PVC flange. A fourteen inch length of 1-1/4 inch PVC pipe was connected to both the up- and downstream sides of the flange. Two pressure taps were constructed of 1/8 inch hose barbs and located one pipe diameter upstream of the orifice plate and one-half pipe diameter downstream in accordance with Sakiadis (1984). In accordance with Brown et al. (1953) a simple flat 1/32 inch thick aluminum plate with a centrally drilled 1/4 inch opening was made with ordinary tools.

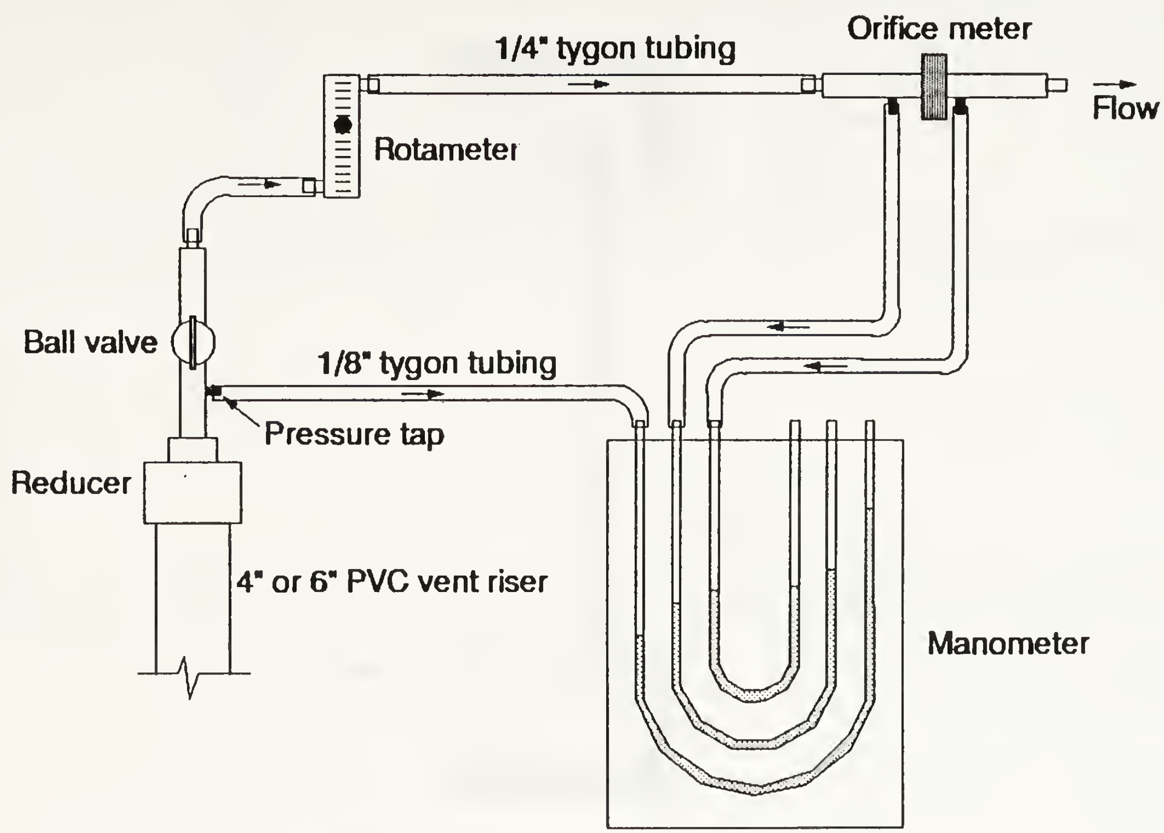



Figure 4-5: Typical Equipment Set-up with Orifice Meter
(Drawing is not to scale)

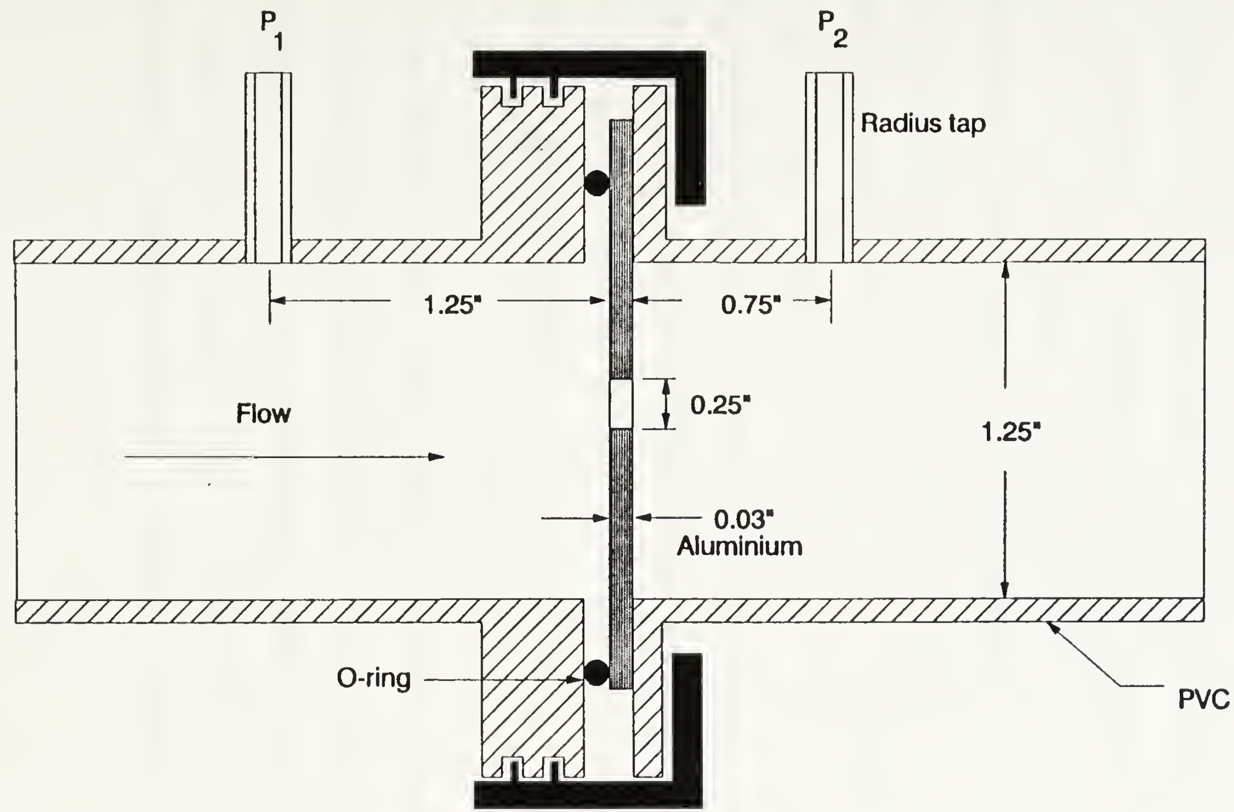



Figure 4-6: Orifice Plate Detail
(Drawing is not to scale)

## METHODS

Gas flow and pressure measurements were taken from each vent to establish an average flow rate. The two capped sections were assumed to be in a steady gas production phase and, therefore, a limited number of measurements were taken from each of the vents associated with each cell. The active section was monitored more frequently in an attempt to identify any potential or dramatic changes in the landfill gas production because of its relatively young age.

Flow and pressure readings were taken after the instrumentation was installed and pressures allowed to stabilize for approximately five minutes. A five minute waiting period was selected to allow the manometer to reach apparent stabilization

The rotameter was calibrated utilizing the downstream orifice meter. The calibration curve for the Gilmont meter and the supporting calculations are presented and discussed in Appendix A. The field measurements and corrected flow values are provided in Appendix B. All flow measurements were converted to standard cubic feet per minute (SCFM).

# CHAPTER 5

# RESULTS AND DISCUSSION

The gas flow measurements are presented in Appendix B. Vents for which the gas flow was below detectable limits of the equipment installed are marked BDL (below detectable limits). BDL values were assumed to be zero for the purpose of calculating the sum of the average flows. The average gas production for each vent was calculated and is provided in Table 5-1. The average flows per vent are also shown graphically in Figure 5-1. Statistical analysis, demonstrated in Appendix C, indicates that the average LFG production rates per vent from the active section and the 11-acre section are the same, however, the production rate of the 30-acre section is significantly lower.

From observations in the field it is known that a significant volume of gas from the active section of the ACSWL is escaping without measurement. Although the installed liner prevents the downward migration of the gases, the lack of a cap allow vertical losses through the soil cover. It was assumed that significant horizontal losses are also present at the northern most face of the active section where refuse

Table 5-1 - Average Flow Values for ACSWL Vents
(as measured from Jul 1991 to Feb 1992)

| VENT ID# | AVERAGE FLOW (SCFM) | | | SUM OF AVERAGE FLOWS (SCFM) | SUM OF AVERAGE FLOWS (SCFD) |
|---|---|---|---|---|---|
| 1 | BDL | | | 2.24 | 3218.72 |
| 2 | BDL | | | | |
| 3 | 1.03 | | | | |
| 4 | 0.83 | | | | |
| 6 | 0.38 | | | | |
| 8 | BDL | | | | |
| I1 | | 0.59 | | 8.84 | 12726.60 |
| I2 | | 0.52 | | | |
| I3 | | 0.51 | | | |
| I4 | | BDL | | | |
| I5 | | 0.82 | | | |
| I6 | | 0.55 | | | |
| I7 | | 0.51 | | | |
| I8 | | 0.89 | | | |
| I10 | | 1.08 | | | |
| I11 | | 0.64 | | | |
| I12 | | 0.65 | | | |
| I13 | | 0.97 | | | |
| I14 | | 0.38 | | | |
| I15 | | 0.39 | | | |
| I16 | | 0.35 | | | |
| GV6 | | | 0.22 | 2.04 | 2941.35 |
| GV7 | | | 0.30 | | |
| GV8 | | | 0.20 | | |
| GV17 | | | 0.26 | | |
| GV18 | | | 0.28 | | |
| GV19 | | | 0.22 | | |
| GV20 | | | 0.20 | | |
| GV29 | | | 0.19 | | |
| GV30 | | | 0.19 | | |
| ALL VENTS | | | | 13.12 | 18886.67 |

NOTES:
(1) Vents not shown from the 30-acre site (GV) had values below detectable limits (BDL) and were omitted from this table.
(2) SCFM conversions are at 1 atm and 60 degrees F.

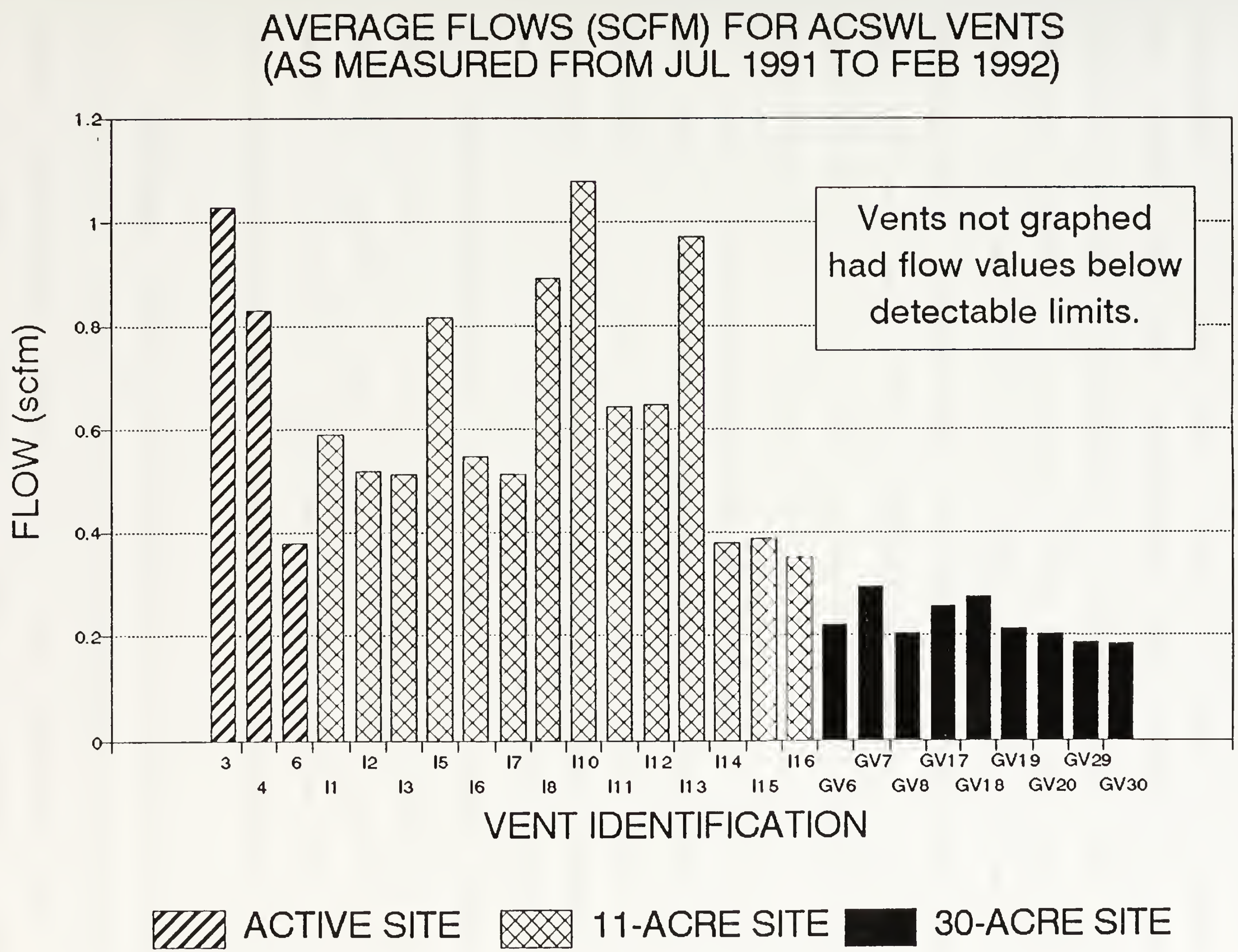

AVERAGE FLOWS (SCFM) FOR ACSWL VENTS
(AS MEASURED FROM JUL 1991 TO FEB 1992)
FLOW (scfm)
1.2
1
0.8
0.6
0.4
0.2
0
Vents not graphed had flow values below detectable limits.
3
4
6
I1
I2
I3
I5
I6
I7
I8
I10
I11
I12
I13
I14
I15
I16
GV6
GV7
GV8
GV17
GV18
GV19
GV20
GV29
GV30
VENT IDENTIFICATION
ACTIVE SITE
11-ACRE SITE
30-ACRE SITE

Figure 5-1

is deposited in vertical lifts. Additionally, the radius of influence for the gas vents in the active section is unknown and was not calculated in this study. Consequently, the flow rates were not extrapolated over the sectional area. An additional complication in the active section was that vents 1 and 2 had near-surface obstructions which were believed to block gas flow through the vent risers disallowing reliable gas flow measurement. These obstructions resulted from below grade separation of the vent pipe extensions and caving of the surrounding gravel, refuse, and soil.

For the above reasons, the gas flow data obtained from the active section was considered questionable and not representative of the actual production rates. The data collected for the 11-acre and 30-acre sections were assumed to be more representative of the actual gas generation rates. It was acknowledged that LFG losses through the unlined sides of these sections as a result of horizontal migration was probable, however, these losses were assumed to be minimal because of the number and close proximity of the vents that was assumed to provide for a path of least resistance for the LFG.

<u>Modeling</u>. Based on the presumption that the rate of gas production is a direct function of microbial activity, the Scholl Canyon model was utilized in the analysis of the 11-acre and 30-acre sections. Appendix D provides a more

detailed discussion of the Scholl Canyon method (Schumacher 1983).

The rate of gas production in the landfill is the summation of the gas production of all the individual unit masses of the refuse. Some of these units were placed at the beginning of the waste disposal operation for each respective section and, therefore, are further along in the decay phase while the later placed refuse may be at the maximum rate of production.

Given the ultimate yield range of 0.2 to 0.25 cubic meters per kilogram of volatile solids (3.2 to 4.0 cubic feet of methane per pound of volatile solids) from Miller et al. (1991a), and the assumed ratio for total volatile solids to total solids in MSW of 0.67 (Ham et al. 1979, Laquidara et al. 1986), the ultimate methane production ($L_o$) can be assumed to be in the range of 2.1 to 2.7 cubic feet per pound of refuse. The stoichiometric calculation of 4.91 cubic feet of total LFG per pound of refuse (discussed in Chapter 3) and the approximation of 60% methane from analysis gas results in a value of 2.9 cubic feet per pound of refuse as the maximum methane yield for the ACSWL.

For the purpose of modeling, the value of 2.1 cubic feet of methane per pound of refuse was utilized as $L_o$. The Scholl Canyon Model was then solved, through trial and error, by adjusting the refuse half-life ($t_{1/2}$) to fit the modeled curve through the assumed methane flow rate, 60% of the measured

Scholl Canyon Model for the 11-acre Section (Lo=2.1 cf/lb, t(1/2)=3.4 years)

| | Year sub-mass deposited | | | |
|---|---|---|---|---|
| Observation Year | 1985 | 1986 | 1987 | Total/year (SCFM) |
| 1985 | 1.44E+03 | | | 1437.71 |
| 1986 | 4.55E+02 | 1.17E+03 | | 1620.93 |
| 1987 | 1.44E+02 | 3.69E+02 | 1.17E+03 | 1678.91 |
| 1988 | 4.56E+01 | 1.17E+02 | 3.69E+02 | 531.29 |
| 1989 | 1.44E+01 | 3.69E+01 | 1.17E+02 | 168.13 |
| 1990 | 4.56E+00 | 1.17E+01 | 3.69E+01 | 53.20 |
| 1991 | 1.44E+00 | 3.70E+00 | 1.17E+01 | 16.84 |
| 1992 | 4.57E-01 | 1.17E+00 | 3.70E+00 | 5.33 |
| 1993 | 1.45E-01 | 3.71E-01 | 1.17E+00 | 1.69 |
| 1994 | 4.58E-02 | 1.17E-01 | 3.71E-01 | 0.53 |
| 1995 | 1.45E-02 | 3.71E-02 | 1.17E-01 | 0.17 |
| 1996 | 4.58E-03 | 1.17E-02 | 3.71E-02 | 0.05 |
| 1997 | 1.45E-03 | 3.72E-03 | 1.17E-02 | 1.69E-02 |
| 1998 | 4.59E-04 | 1.18E-03 | 3.72E-03 | 5.35E-03 |
| 1999 | 1.45E-04 | 3.72E-04 | 1.18E-03 | 1.69E-03 |
| 2000 | 4.59E-05 | 1.18E-04 | 3.72E-04 | 5.36E-04 |
| 2001 | 1.45E-05 | 3.73E-05 | 1.18E-04 | 1.70E-04 |
| 2002 | 4.60E-06 | 1.18E-05 | 3.73E-05 | 5.37E-05 |
| 2003 | 1.46E-06 | 3.73E-06 | 1.18E-05 | 1.70E-05 |
| 2004 | 4.61E-07 | 1.18E-06 | 3.73E-06 | 5.37E-06 |
| 2005 | 1.46E-07 | 3.74E-07 | 1.18E-06 | 1.70E-06 |
| 2006 | 4.61E-08 | 1.18E-07 | 3.74E-07 | 5.38E-07 |
| 2007 | 1.46E-08 | 3.74E-08 | 1.18E-07 | 1.70E-07 |
| 2008 | 4.62E-09 | 1.18E-08 | 3.74E-08 | 5.39E-08 |
| 2009 | 1.46E-09 | 3.75E-09 | 1.18E-08 | 1.70E-08 |
| 2010 | 4.63E-10 | 1.19E-09 | 3.75E-09 | 5.40E-09 |
| 2011 | 1.46E-10 | 3.75E-10 | 1.19E-09 | 1.71E-09 |
| 2012 | 4.63E-11 | 1.19E-10 | 3.75E-10 | 5.40E-10 |
| 2013 | 1.47E-11 | 3.76E-11 | 1.19E-10 | 1.71E-10 |
| 2014 | 4.64E-12 | 1.19E-11 | 3.76E-11 | 5.41E-11 |
| 2015 | 1.47E-12 | 3.76E-12 | 1.19E-11 | 1.71E-11 |
| 2016 | 4.65E-13 | 1.19E-12 | 3.76E-12 | 5.42E-12 |
| 2017 | 1.47E-13 | 3.77E-13 | 1.19E-12 | 1.71E-12 |
| 2018 | 4.65E-14 | 1.19E-13 | 3.77E-13 | 5.43E-13 |
| 2019 | 1.47E-14 | 3.77E-14 | 1.19E-13 | 1.72E-13 |
| 2020 | 4.66E-15 | 1.19E-14 | 3.77E-14 | 5.43E-14 |

Table 5-2

Scholl Canyon Model for the 30-acre Section (Lo=2.1 cf/lb, t(1/2)=4.36 years)

| Observation Year | Year sub-mass deposited 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | Total/year (SCFM) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1972 | 4.32E+02 | | | | | | | | | | | | | 432.025 |
| 1973 | 1.76E+02 | 5.30E+02 | | | | | | | | | | | | 706.297 |
| 1974 | 7.18E+01 | 2.16E+02 | 5.71E+02 | | | | | | | | | | | 858.897 |
| 1975 | 2.93E+01 | 8.81E+01 | 2.33E+02 | 6.12E+02 | | | | | | | | | | 961.892 |
| 1976 | 1.19E+01 | 3.59E+01 | 9.49E+01 | 2.49E+02 | 8.16E+02 | | | | | | | | | 1207.792 |
| 1977 | 4.87E+00 | 1.46E+01 | 3.87E+01 | 1.02E+02 | 3.49E+02 | 8.93E+02 | | | | | | | | 1202.322 |
| 1978 | 1.98E+00 | 5.97E+00 | 1.58E+01 | 4.15E+01 | 1.49E+02 | 2.83E+02 | 7.34E+02 | | | | | | | 1231.027 |
| 1979 | 8.09E-01 | 2.43E+00 | 6.43E+00 | 1.69E+01 | 8.36E+01 | 1.15E+02 | 2.99E+02 | 7.75E+02 | | | | | | 1279.496 |
| 1980 | 3.30E-01 | 9.92E-01 | 2.62E+00 | 6.89E+00 | 2.70E+01 | 4.70E+01 | 1.22E+02 | 3.16E+02 | 8.16E+02 | | | | | 1338.402 |
| 1981 | 1.34E-01 | 4.05E-01 | 1.07E+00 | 2.81E+00 | 0.00E+00 | 1.92E+01 | 4.97E+01 | 1.29E+02 | 3.33E+02 | 8.56E+02 | | | | 1391.049 |
| 1982 | 5.48E-02 | 1.65E-01 | 4.36E-01 | 1.15E+00 | 4.36E+01 | 7.81E+00 | 2.03E+01 | 5.25E+01 | 1.36E+02 | 3.49E+02 | 8.97E+02 | | | 1507.872 |
| 1983 | 2 23E-02 | 6.72E-02 | 1.78E-01 | 4.67E-01 | 0.00E+00 | 3.18E+00 | 8.27E+00 | 2.14E+01 | 5.53E+01 | 1.42E+02 | 3.66E+02 | 9.38E+02 | | 1534.971 |
| 1984 | 9.11E-03 | 2.74E-02 | 7.24E-02 | 1.90E-01 | 0.00E+00 | 1.30E+00 | 3.37E+00 | 8.73E+00 | 2.25E+01 | 5.80E+01 | 1.49E+02 | 3.82E+02 | 9.79E+02 | 1604.557 |
| 1985 | 3.71E-03 | 1.12E-02 | 2.95E-02 | 7.76E-02 | 0.00E+00 | 5.29E-01 | 1.37E+00 | 3.56E+00 | 9.19E+00 | 2.37E+01 | 6.08E+01 | 1.56E+02 | 3.99E+02 | 854.159 |
| 1986 | 1.51E-03 | 4.56E-03 | 1.20E-02 | 3.16E-02 | 0.00E+00 | 2.16E-01 | 5.60E-01 | 1.45E+00 | 3.75E+00 | 9.65E+00 | 2.48E+01 | 6.36E+01 | 1.63E+02 | 266.693 |
| 1987 | 6.17E-04 | 1.86E-03 | 4.91E-03 | 1.29E-02 | 0.00E+00 | 8.79E-02 | 2.28E-01 | 5.91E-01 | 1.53E+00 | 3 93E+00 | 1.01E+01 | 2.59E+01 | 6.63E+01 | 108.727 |
| 1988 | 2.52E-04 | 7.57E-04 | 2.00E-03 | 5.26E-03 | 2.36E-02 | 3.59E-02 | 9.31E-02 | 2.41E-01 | 6.22E-01 | 1.60E+00 | 4.12E+00 | 1.06E+01 | 2.70E+01 | 44.351 |
| 1989 | 1.03E-04 | 3.09E-04 | 8.16E-04 | 2.14E-03 | 7.82E-03 | 1.46E-02 | 3.80E-02 | 9.83E-02 | 2.54E-01 | 6.54E-01 | 1.68E+00 | 4.31E+00 | 1.10E+01 | 18.079 |
| 1990 | 4.18E-05 | 1.26E-04 | 3.33E-04 | 8.74E-04 | 3.19E-03 | 5.96E-03 | 1.55E-02 | 4.01E-02 | 1.03E-01 | 2.66E-01 | 6.85E-01 | 1.76E+00 | 4.49E+00 | 7.371 |
| 1991 | 1.71E-05 | 5.13E-05 | 1.36E-04 | 3.56E-04 | 0.00E+00 | 2.43E-03 | 6.31E-03 | 1.63E-02 | 4.22E-02 | 1.09E-01 | 2.79E-01 | 7.16E-01 | 1.83E+00 | 3.004 |
| 1992 | 6.95E-06 | 2.09E-05 | 5.53E-05 | 1.45E-04 | 1.71E-03 | 9.90E-04 | 2.57E-03 | 6.66E-03 | 1.72E-02 | 4.43E-02 | 1.14E-01 | 2.92E-01 | 7.47E-01 | 1.226 |
| 1993 | 2.83E-06 | 8.53E-06 | 2.25E-05 | 5.92E-05 | 0.00E+00 | 4.04E-04 | 1.05E-03 | 2.72E-03 | 7.01E-03 | 1.81E-02 | 4.64E-02 | 1.19E-01 | 3.05E-01 | 0.499 |
| 1994 | 1.16E-06 | 3.48E-06 | 9.19E-06 | 2.41E-05 | 0.00E+00 | 1.65E-04 | 4.28E-04 | 1.11E-03 | 2.86E-03 | 7.36E-03 | 1.89E-02 | 4.85E-02 | 1.24E-01 | 0.204 |
| 1995 | 4.71E-07 | 1.42E-06 | 3.75E-06 | 9.84E-06 | 0.00E+00 | 6.71E-05 | 1.74E-04 | 4.51E-04 | 1.17E-03 | 3.00E-03 | 7.71E-03 | 1.98E-02 | 5.06E-02 | 0.083 |
| 1996 | 1.92E-07 | 5.78E-07 | 1.53E-06 | 4.01E-06 | 0.00E+00 | 2.74E-05 | 7.11E-05 | 1.84E-04 | 4.75E-04 | 1.22E-03 | 3.14E-03 | 8.06E-03 | 2.06E-02 | 0.034 |
| 1997 | 7.83E-08 | 2.36E-07 | 6 23E-07 | 1.64E-06 | 4.52E-06 | 1.12E-05 | 2.90E-05 | 7.50E-05 | 1.94E-04 | 4.99E-04 | 1.28E-03 | 3 29E-03 | 8.41E-03 | 0.014 |
| 1998 | 3.19E-08 | 9.61E-08 | 2.54E-07 | 6.67E-07 | 2.30E-06 | 4.55E-06 | 1.18E-05 | 3.06E-05 | 7.90E-05 | 2.03E-04 | 5.23E-04 | 1.34E-03 | 3.43E-03 | 0.006 |
| 1999 | 1.30E-08 | 3.92E-08 | 1.03E-07 | 2.72E-07 | 9.72E-07 | 1.85E-06 | 4.82E-06 | 1.25E-05 | 3.22E-05 | 8.29E-05 | 2.13E-04 | 5.46E-04 | 1.40E-03 | 0.002 |
| 2000 | 5.31E-09 | 1.60E-08 | 4.22E-08 | 1.11E-07 | 3.84E-07 | 7.56E-07 | 1.96E-06 | 5.08E-06 | 1.31E-05 | 3.38E-05 | 8 69E-05 | 2.23E-04 | 5.70E-04 | 0.001 |

Table 5-3

flow rates, for both the 11- and 30-acre sections. The 11- and 30-acre sections were determined to have $t_{1/2}$ values of 3.4 and 4.36 years, respectively. Tables 5-2 and 5-3 contain the flow rate values for the models discussed above.

A weighted average of the half-lives was determined on a total tonnage basis. The data used in the calculations for the weighted average are presented in the table below:

| | 30-acre | 11-acre | Totals |
|---|---|---|---|
| Tonnage Per Section | 1,322,992 | 410,000 | 1,732,992 |
| % of Total Tonnage | 76.3 | 23.7 | 100 |
| Half-life (from model) | 4.36 | 3.4 | - |

The weighted value of $t_{1/2}$ is equal to 4.13 years and was calculated by summing the products of the modeled half-lives and their respective % of total tonnage values. Using this weighted half-life and the assumed $L_0$ value of 2.1 cubic feet of methane per pound, Figures 5-2 through 5-4, were developed for the prediction of the ultimate methane production as a function of landfill age for the 11-acre, 30-acre, and active sections. Tables 5-4 through 5-6 are the respective data tables for the figures above. Figure 5-5 is a graphical composite of the models for the three individual sections. Although there are an infinite number of possible solutions to the Scholl Canyon technique that would fit the actual flows

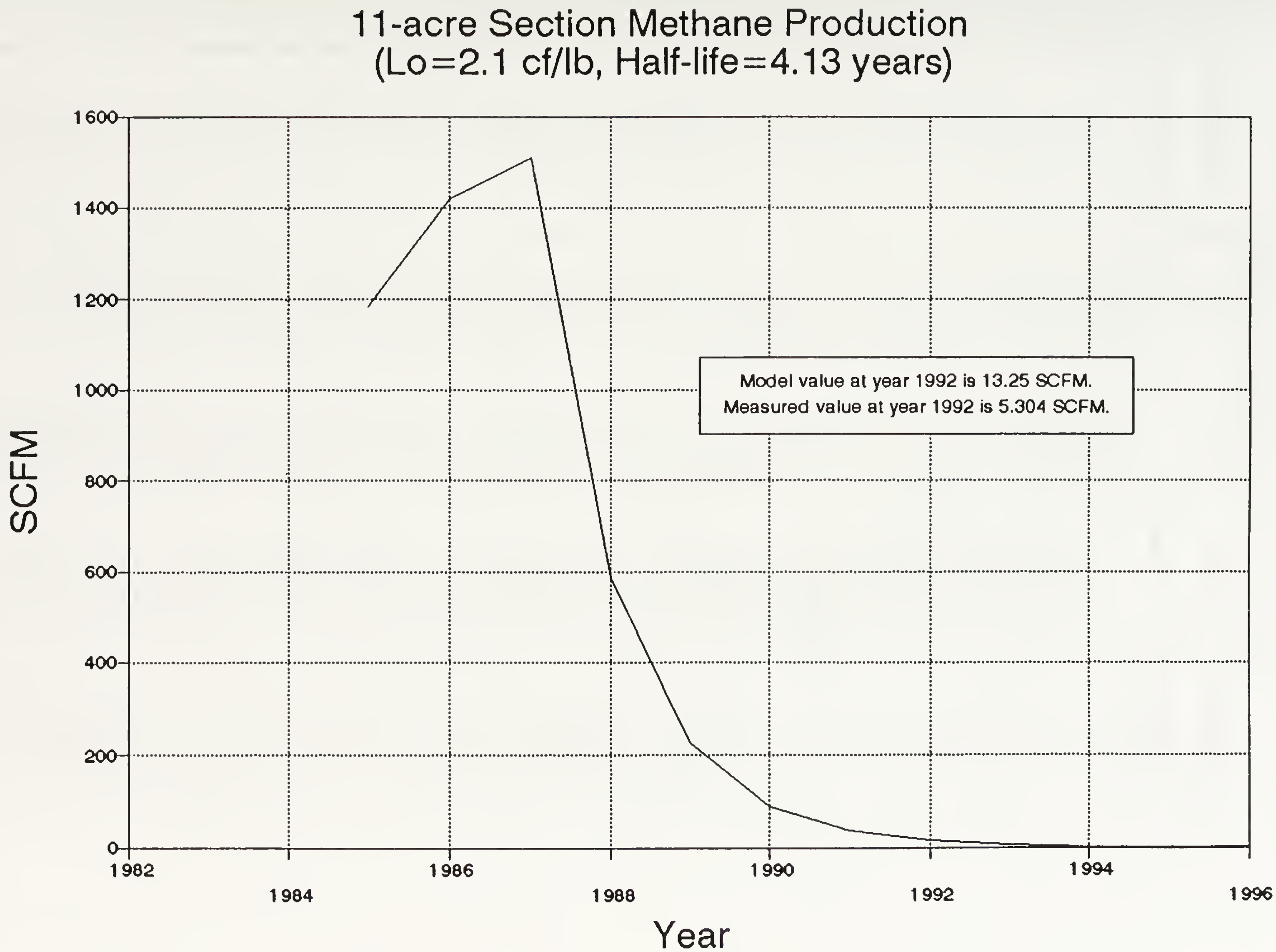

11-acre Section Methane Production
(Lo=2.1 cf/lb, Half-life=4.13 years)
Model value at year 1992 is 13.25 SCFM.
Measured value at year 1992 is 5.304 SCFM.
SCFM
0
200
400
600
800
1000
1200
1400
1600
1982
1984
1986
1988
1990
1992
1994
1996
Year

Figure 5-2

Scholl Canyon Model for the 11-acre Section (Lo=2.1 cf/lb, t(1/2)=4.13 years)

| Observation Year | Year sub-mass deposited 1985 | 1986 | 1987 | Total/year (SCFM) |
|---|---|---|---|---|
| 1985 | 1.18E+03 | | | 1183.58 |
| 1986 | 4.59E+02 | 9.60E+02 | | 1418.89 |
| 1987 | 1.78E+02 | 3.72E+02 | 9.60E+02 | 1510.15 |
| 1988 | 6.90E+01 | 1.44E+02 | 3.72E+02 | 585.66 |
| 1989 | 2.68E+01 | 5.60E+01 | 1.44E+02 | 227.13 |
| 1990 | 1.04E+01 | 2.17E+01 | 5.60E+01 | 88.08 |
| 1991 | 4.03E+00 | 8.42E+00 | 2.17E+01 | 34.16 |
| 1992 | 1.56E+00 | 3.27E+00 | 8.42E+00 | 13.25 |
| 1993 | 6.06E-01 | 1.27E+00 | 3.27E+00 | 5.14 |
| 1994 | 2.35E-01 | 4.91E-01 | 1.27E+00 | 1.99 |
| 1995 | 9.11E-02 | 1.90E-01 | 4.91E-01 | 0.77 |
| 1996 | 3.53E-02 | 7.39E-02 | 1.90E-01 | 0.30 |
| 1997 | 1.37E-02 | 2.86E-02 | 7.39E-02 | 1.16E-01 |
| 1998 | 5.31E-03 | 1.11E-02 | 2.86E-02 | 4.51E-02 |
| 1999 | 2.06E-03 | 4.31E-03 | 1.11E-02 | 1.75E-02 |
| 2000 | 7.99E-04 | 1.67E-03 | 4.31E-03 | 6.78E-03 |
| 2001 | 3.10E-04 | 6.48E-04 | 1.67E-03 | 2.63E-03 |
| 2002 | 1.20E-04 | 2.51E-04 | 6.48E-04 | 1.02E-03 |
| 2003 | 4.66E-05 | 9.75E-05 | 2.51E-04 | 3.95E-04 |
| 2004 | 1.81E-05 | 3.78E-05 | 9.75E-05 | 1.53E-04 |
| 2005 | 7.01E-06 | 1.47E-05 | 3.78E-05 | 5.95E-05 |
| 2006 | 2.72E-06 | 5.69E-06 | 1.47E-05 | 2.31E-05 |
| 2007 | 1.05E-06 | 2.20E-06 | 5.69E-06 | 8.94E-06 |
| 2008 | 4.09E-07 | 8.55E-07 | 2.20E-06 | 3.47E-06 |
| 2009 | 1.59E-07 | 3.32E-07 | 8.55E-07 | 1.35E-06 |
| 2010 | 6.15E-08 | 1.29E-07 | 3.32E-07 | 5.22E-07 |
| 2011 | 2.39E-08 | 4.99E-08 | 1.29E-07 | 2.02E-07 |
| 2012 | 9.25E-09 | 1.93E-08 | 4.99E-08 | 7.85E-08 |
| 2013 | 3.59E-09 | 7.50E-09 | 1.93E-08 | 3.04E-08 |
| 2014 | 1.39E-09 | 2.91E-09 | 7.50E-09 | 1.18E-08 |
| 2015 | 5.40E-10 | 1.13E-09 | 2.91E-09 | 4.58E-09 |
| 2016 | 2.09E-10 | 4.38E-10 | 1.13E-09 | 1.78E-09 |
| 2017 | 8.11E-11 | 1.70E-10 | 4.38E-10 | 6.88E-10 |
| 2018 | 3.15E-11 | 6.58E-11 | 1.70E-10 | 2.67E-10 |
| 2019 | 1.22E-11 | 2.55E-11 | 6.58E-11 | 1.04E-10 |
| 2020 | 4.73E-12 | 9.90E-12 | 2.55E-11 | 4.02E-11 |

Table 5-4

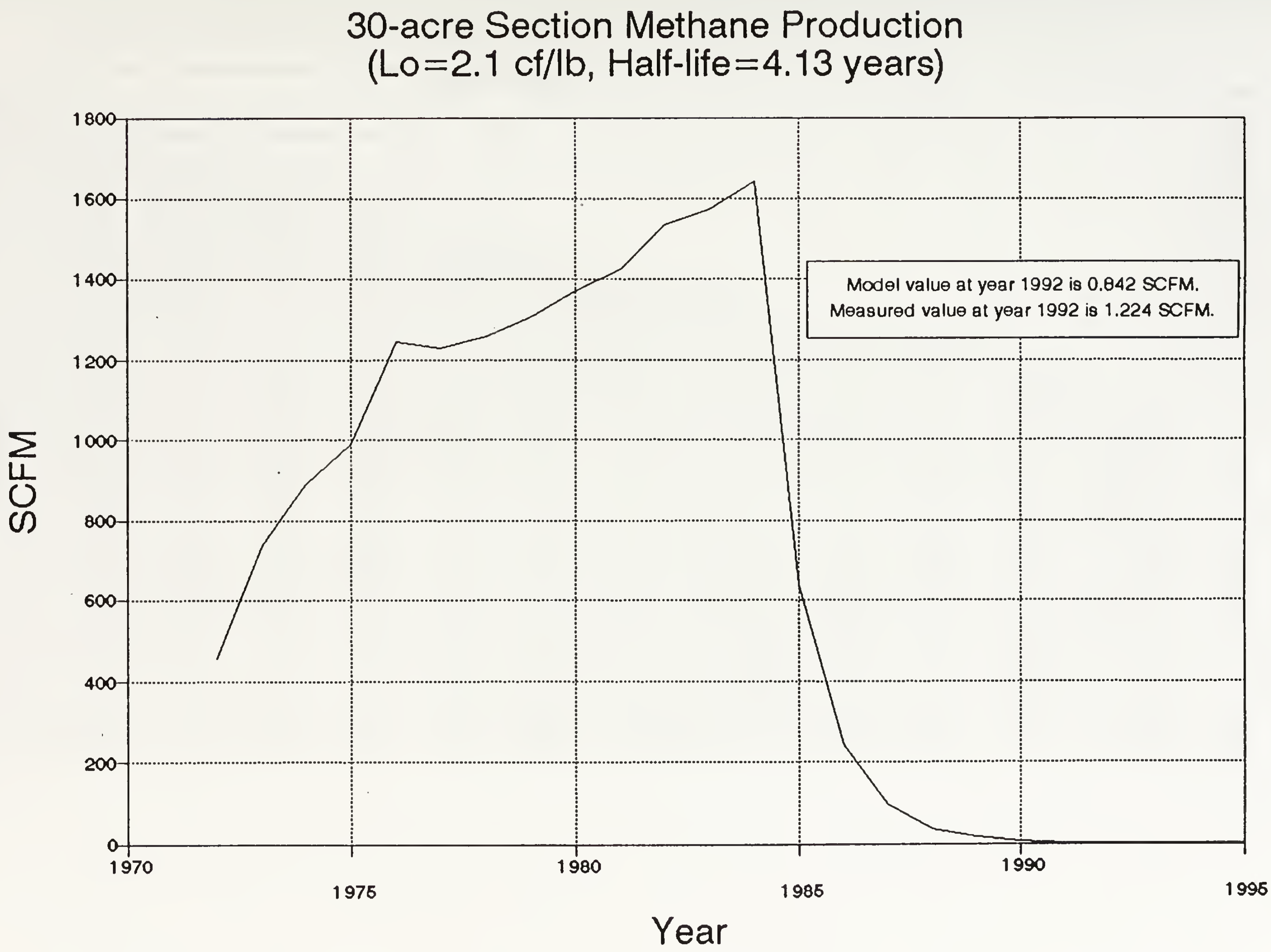

30-acre Section Methane Production
(Lo=2.1 cf/lb, Half-life=4.13 years)
Model value at year 1992 is 0.842 SCFM.
Measured value at year 1992 is 1.224 SCFM.
SCFM
1800
1600
1400
1200
1000
800
600
400
200
0
1970
1975
1980
1985
1990
1995
Year

Figure 5-3

Scholl Canyon Model for the 30-acre Section (Lo=2.1 cf/lb, t(1/2)=4.13 years)

| Observation Year | Year sub-mass deposited 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 1980 | 1981 | 1982 | 1983 | 1984 | Total/year (SCFM) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1972 | 4.56E+02 | | | | | | | | | | | | | 456.085 |
| 1973 | 1.77E+02 | 5.60E+02 | | | | | | | | | | | | 736.568 |
| 1974 | 6.86E+01 | 2.17E+02 | 6.03E+02 | | | | | | | | | | | 888.398 |
| 1975 | 2.66E+01 | 8.42E+01 | 2.34E+02 | 6.46E+02 | | | | | | | | | | 990.333 |
| 1976 | 1.03E+01 | 3.26E+01 | 9.07E+01 | 2.50E+02 | 8.61E+02 | | | | | | | | | 1245.131 |
| 1977 | 4.00E+00 | 1.27E+01 | 3.52E+01 | 9.71E+01 | 3.51E+02 | 7.32E+02 | | | | | | | | 1231.484 |
| 1978 | 1.55E+00 | 4.91E+00 | 1.36E+01 | 3.77E+01 | 1.42E+02 | 2.84E+02 | 7.75E+02 | | | | | | | 1259.022 |
| 1979 | 6.02E-01 | 1.90E+00 | 5.29E+00 | 1.46E+01 | 5.78E+01 | 1.10E+02 | 3.01E+02 | 8.18E+02 | | | | | | 1308.792 |
| 1980 | 2.33E-01 | 7.38E-01 | 2.05E+00 | 5.67E+00 | 2.34E+01 | 4.27E+01 | 1.17E+02 | 3.17E+02 | 8.61E+02 | | | | | 1369.609 |
| 1981 | 9.05E-02 | 2.86E-01 | 7.95E-01 | 2.20E+00 | 0.00E+00 | 1.66E+01 | 4.52E+01 | 1.23E+02 | 3.34E+02 | 9.04E+02 | | | | 1426.209 |
| 1982 | 3.51E-02 | 1.11E-01 | 3.08E-01 | 8.52E-01 | 3.41E+01 | 6.42E+00 | 1.75E+01 | 4.77E+01 | 1.30E+02 | 3.51E+02 | 9.47E+02 | | | 1534.347 |
| 1983 | 1.36E-02 | 4.31E-02 | 1.20E-01 | 3.30E-01 | 0.00E+00 | 2.49E+00 | 6.80E+00 | 1.85E+01 | 5.02E+01 | 1.36E+02 | 3.67E+02 | 9.90E+02 | | 1572.056 |
| 1984 | 5.28E-03 | 1.67E-02 | 4.64E-02 | 1.28E-01 | 0.00E+00 | 9.66E-01 | 2.64E+00 | 7.18E+00 | 1.95E+01 | 5.27E+01 | 1.42E+02 | 3.84E+02 | 1.03E+03 | 1642.946 |
| 1985 | 2.05E-03 | 6.48E-03 | 1.80E-02 | 4.97E-02 | 0.00E+00 | 3.75E-01 | 1.02E+00 | 2.78E+00 | 7.55E+00 | 2.05E+01 | 5.52E+01 | 1.49E+02 | 4.01E+02 | 637.163 |
| 1986 | 7.94E-04 | 2.51E-03 | 6.98E-03 | 1.93E-02 | 0.00E+00 | 1.45E-01 | 3.97E-01 | 1.08E+00 | 2.93E+00 | 7.93E+00 | 2.14E+01 | 5.78E+01 | 1.55E+02 | 247.103 |
| 1987 | 3.08E-04 | 9.74E-04 | 2.71E-03 | 7.48E-03 | 0.00E+00 | 5.63E-02 | 1.54E-01 | 4.19E-01 | 1.14E+00 | 3.08E+00 | 8.31E+00 | 2.24E+01 | 6.03E+01 | 95.631 |
| 1988 | 1.19E-04 | 3.78E-04 | 1.05E-03 | 2.90E-03 | 1.37E-02 | 2.18E-02 | 5.96E-02 | 1.62E-01 | 4.41E-01 | 1.19E+00 | 3.22E+00 | 8.69E+00 | 2.34E+01 | 37.178 |
| 1989 | 4.63E-05 | 1.47E-04 | 4.07E-04 | 1.12E-03 | 4.31E-03 | 8.47E-03 | 2.31E-02 | 6.30E-02 | 1.71E-01 | 4.63E-01 | 1.25E+00 | 3.37E+00 | 9.06E+00 | 14.417 |
| 1990 | 1.80E-05 | 5.68E-05 | 1.58E-04 | 4.36E-04 | 1.67E-03 | 3.29E-03 | 8.97E-03 | 2.44E-02 | 6.63E-02 | 1.79E-01 | 4.85E-01 | 1.31E+00 | 3.52E+00 | 5.591 |
| 1991 | 6.97E-06 | 2.20E-05 | 6.12E-05 | 1.69E-04 | 0.00E+00 | 1.27E-03 | 3.48E-03 | 9.47E-03 | 2.57E-02 | 6.96E-02 | 1.88E-01 | 5.07E-01 | 1.36E+00 | 2.168 |
| 1992 | 2.70E-06 | 8.55E-06 | 2.37E-05 | 8.56E-05 | 8.13E-04 | 4.94E-04 | 1.35E-03 | 3.67E-03 | 9.97E-03 | 2.70E-02 | 7.29E-02 | 1.97E-01 | 5.29E-01 | 0.842 |
| 1993 | 1.05E-06 | 3.32E-06 | 9.21E-06 | 2.54E-05 | 0.00E+00 | 1.92E-04 | 5.23E-04 | 1.42E-03 | 3.87E-03 | 1.05E-02 | 2.83E-02 | 7.62E-02 | 2.05E-01 | 0.326 |
| 1994 | 4.06E-07 | 1.29E-06 | 3.57E-06 | 9.86E-06 | 0.00E+00 | 7.43E-05 | 2.03E-04 | 5.52E-04 | 1.50E-03 | 4.06E-03 | 1.10E-02 | 2.96E-02 | 7.95E-02 | 0.126 |
| 1995 | 1.58E-07 | 4.99E-07 | 1.38E-06 | 3.83E-06 | 0.00E+00 | 2.88E-05 | 7.87E-05 | 2.14E-04 | 5.81E-04 | 1.57E-03 | 4.25E-03 | 1.15E-02 | 3.08E-02 | 0.049 |
| 1996 | 6.11E-08 | 1.93E-07 | 5.37E-07 | 1.48E-06 | 0.00E+00 | 1.12E-05 | 3.05E-05 | 8.31E-05 | 2.25E-04 | 6.10E-04 | 1.65E-03 | 4.45E-03 | 1.20E-02 | 0.019 |
| 1997 | 2.37E-08 | 7.50E-08 | 2.08E-07 | 5.75E-07 | 1.67E-06 | 4.34E-06 | 1.18E-05 | 3.22E-05 | 8.74E-05 | 2.37E-04 | 6.39E-04 | 1.72E-03 | 4.64E-03 | 0.007 |
| 1998 | 9.19E-09 | 2.91E-08 | 8.08E-08 | 2.23E-07 | 8.09E-07 | 1.68E-06 | 4.59E-06 | 1.25E-05 | 3.39E-05 | 9.18E-05 | 2.48E-04 | 6.69E-04 | 1.80E-03 | 0.003 |
| 1999 | 3.56E-09 | 1.13E-08 | 3.13E-08 | 8.65E-08 | 3.25E-07 | 6.52E-07 | 1.78E-06 | 4.85E-06 | 1.32E-05 | 3.56E-05 | 9.62E-05 | 2.59E-04 | 6.98E-04 | 0.001 |
| 2000 | 1.38E-09 | 4.37E-09 | 1.21E-08 | 3.36E-08 | 1.22E-07 | 2.53E-07 | 6.90E-07 | 1.88E-06 | 5.10E-06 | 1.38E-05 | 3.73E-05 | 1.01E-04 | 2.71E-04 | 0.000 |

Table 5-5

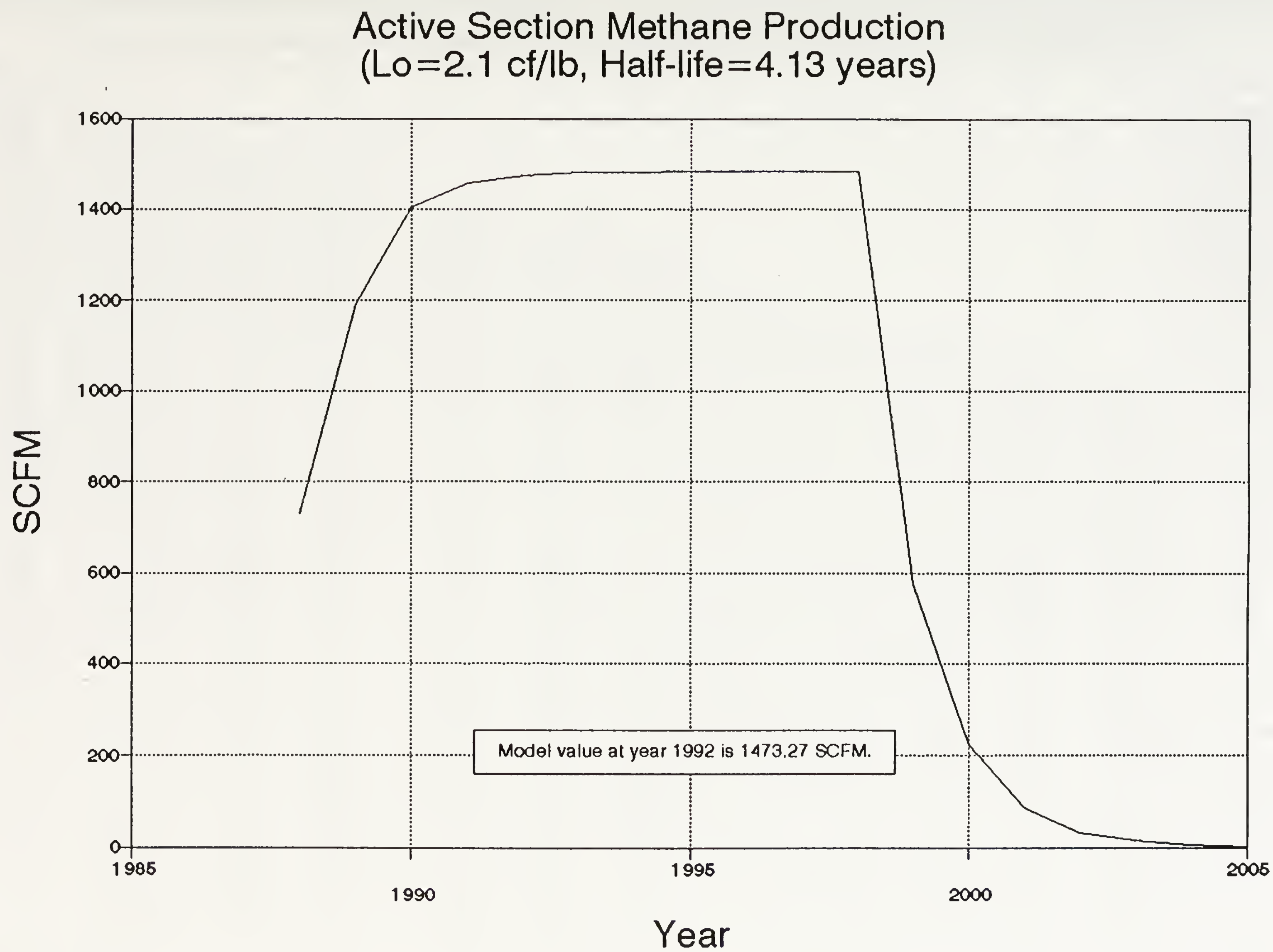
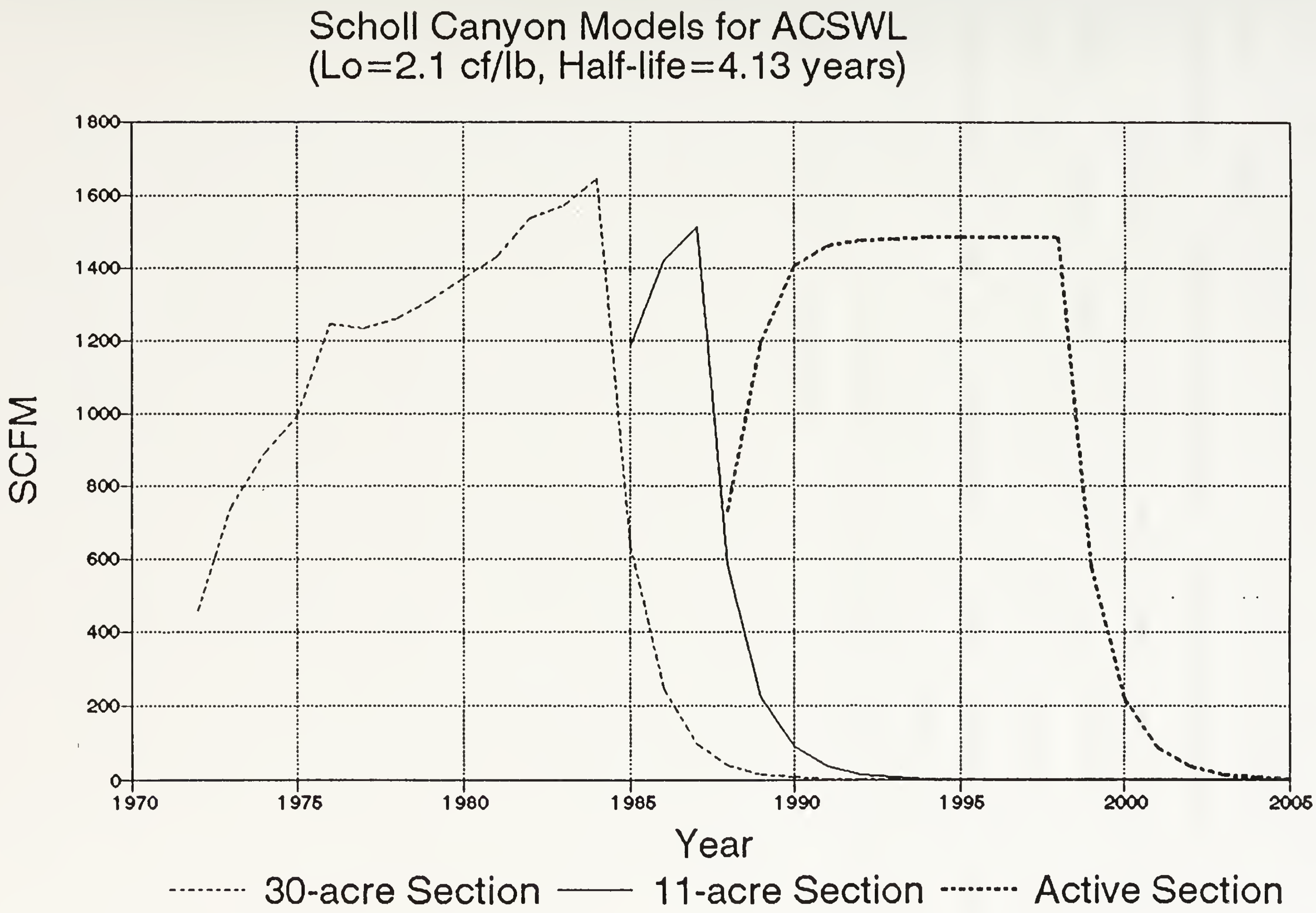

Active Section Methane Production
(Lo=2.1 cf/lb, Half-life=4.13 years)
SCFM
1600
1400
1200
1000
800
600
400
200
0
1985
1990
1995
2000
2005
Year
Model value at year 1992 is 1473.27 SCFM.

Figure 5-4

Scholl Canyon Model for the Active Section (Lo=2.1 cf/lb, t(1/2)=4.13 years)

| Observation Year | Year sub-mass deposited 1988 | 1989 | 1990 | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | Total/year (SCFM) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1988 | 7.28E+02 | | | | | | | | | | | 727.672 |
| 1989 | 2.82E+02 | 9.08E+02 | | | | | | | | | | 1190.400 |
| 1990 | 1.09E+02 | 3.52E+02 | 9.41E+02 | | | | | | | | | 1402.885 |
| 1991 | 4.24E+01 | 1.37E+02 | 3.65E+02 | 9.13E+02 | | | | | | | | 1456.813 |
| 1992 | 1.65E+01 | 5.30E+01 | 1.42E+02 | 3.54E+02 | 9.08E+02 | | | | | | | 1473.272 |
| 1993 | 6.38E+00 | 2.05E+01 | 5.49E+01 | 1.37E+02 | 3.52E+02 | 9.08E+02 | | | | | | 1479.854 |
| 1994 | 2.48E+00 | 7.97E+00 | 2.13E+01 | 5.32E+01 | 1.37E+02 | 3.52E+02 | 9.08E+02 | | | | | 1482.130 |
| 1995 | 9.60E-01 | 3.09E+00 | 8.26E+00 | 2.08E+01 | 5.30E+01 | 1.37E+02 | 3.52E+02 | 9.08E+02 | | | | 1483.090 |
| 1996 | 3.72E-01 | 1.20E+00 | 3.20E+00 | 8.01E+00 | 2.05E+01 | 5.30E+01 | 1.37E+02 | 3.52E+02 | 9.08E+02 | | | 1483.482 |
| 1997 | 1.44E-01 | 4.65E-01 | 1.24E+00 | 3.11E+00 | 7.97E+00 | 2.05E+01 | 5.30E+01 | 1.37E+02 | 3.52E+02 | 9.08E+02 | | 1483.808 |
| 1998 | 5.60E-02 | 1.80E-01 | 4.82E-01 | 1.20E+00 | 3.09E+00 | 7.97E+00 | 2.05E+01 | 5.30E+01 | 1.37E+02 | 3.52E+02 | 9.08E+02 | 1483.662 |
| 1999 | 2.17E-02 | 6.99E-02 | 1.87E-01 | 4.87E-01 | 1.20E+00 | 3.09E+00 | 7.97E+00 | 2.05E+01 | 5.30E+01 | 1.37E+02 | 3.52E+02 | 575.390 |
| 2000 | 8.42E-03 | 2.71E-02 | 7.24E-02 | 1.81E-01 | 4.65E-01 | 1.20E+00 | 3.09E+00 | 7.97E+00 | 2.05E+01 | 5.30E+01 | 1.37E+02 | 223.146 |
| 2001 | 3.27E-03 | 1.05E-02 | 2.81E-02 | 7.03E-02 | 1.80E-01 | 4.65E-01 | 1.20E+00 | 3.09E+00 | 7.97E+00 | 2.05E+01 | 5.30E+01 | 86.540 |
| 2002 | 1.27E-03 | 4.08E-03 | 1.09E-02 | 2.72E-02 | 6.99E-02 | 1.80E-01 | 4.65E-01 | 1.20E+00 | 3.09E+00 | 7.97E+00 | 2.05E+01 | 33.562 |
| 2003 | 4.91E-04 | 1.58E-03 | 4.22E-03 | 1.06E-02 | 2.71E-02 | 6.99E-02 | 1.80E-01 | 4.65E-01 | 1.20E+00 | 3.09E+00 | 7.97E+00 | 13.016 |
| 2004 | 1.91E-04 | 6.13E-04 | 1.64E-03 | 4.10E-03 | 1.05E-02 | 2.71E-02 | 8.99E-02 | 1.80E-01 | 4.85E-01 | 1.20E+00 | 3.09E+00 | 5.048 |
| 2005 | 7.39E-05 | 2.38E-04 | 8.35E-04 | 1.59E-03 | 4.08E-03 | 1.05E-02 | 2.71E-02 | 6.99E-02 | 1.80E-01 | 4.85E-01 | 1.20E+00 | 1.958 |
| 2006 | 2.87E-05 | 9.22E-05 | 2.46E-04 | 6.16E-04 | 1.58E-03 | 4.08E-03 | 1.05E-02 | 2.71E-02 | 6.99E-02 | 1.80E-01 | 4.85E-01 | 0.759 |
| 2007 | 1.11E-05 | 3.58E-05 | 9.58E-05 | 2.39E-04 | 8.13E-04 | 1.58E-03 | 4.08E-03 | 1.05E-02 | 2.71E-02 | 8.99E-02 | 1.80E-01 | 0.294 |
| 2008 | 4.31E-06 | 1.39E-05 | 3.71E-05 | 9.27E-05 | 2.38E-04 | 6.13E-04 | 1.58E-03 | 4.08E-03 | 1.05E-02 | 2.71E-02 | 8.99E-02 | 0.114 |
| 2009 | 1.87E-06 | 5.38E-06 | 1.44E-05 | 3.59E-05 | 9.22E-05 | 2.38E-04 | 6.13E-04 | 1.58E-03 | 4.08E-03 | 1.05E-02 | 2.71E-02 | 0.044 |
| 2010 | 6.48E-07 | 2.09E-06 | 5.57E-08 | 1.39E-05 | 3.58E-05 | 9.22E-05 | 2.38E-04 | 8.13E-04 | 1.58E-03 | 4.08E-03 | 1.05E-02 | 0.017 |
| 2011 | 2.51E-07 | 8.09E-07 | 2.16E-08 | 5.41E-08 | 1.39E-05 | 3.58E-05 | 9.22E-05 | 2.38E-04 | 8.13E-04 | 1.58E-03 | 4.08E-03 | 0.007 |
| 2012 | 9.75E-08 | 3.14E-07 | 8.38E-07 | 2.10E-08 | 5.38E-06 | 1.39E-05 | 3.58E-05 | 9.22E-05 | 2.38E-04 | 6.13E-04 | 1.58E-03 | 0.003 |
| 2013 | 3.78E-08 | 1.22E-07 | 3.25E-07 | 8.13E-07 | 2.09E-08 | 5.38E-06 | 1.39E-05 | 3.58E-05 | 9.22E-05 | 2.38E-04 | 6.13E-04 | 0.001 |
| 2014 | 1.47E-08 | 4.72E-08 | 1.26E-07 | 3.15E-07 | 8.09E-07 | 2.09E-06 | 5.38E-06 | 1.39E-05 | 3.58E-05 | 9.22E-05 | 2.38E-04 | 3.88E-04 |
| 2015 | 5.69E-09 | 1.83E-08 | 4.89E-08 | 1.22E-07 | 3.14E-07 | 8.09E-07 | 2.09E-06 | 5.38E-06 | 1.39E-05 | 3.58E-05 | 9.22E-05 | 1.51E-04 |
| 2016 | 2.21E-09 | 7.10E-09 | 1.90E-08 | 4.74E-08 | 1.22E-07 | 3.14E-07 | 8.09E-07 | 2.09E-06 | 5.38E-06 | 1.39E-05 | 3.58E-05 | 5.84E-05 |
| 2017 | 8.55E-10 | 2.75E-09 | 7.35E-09 | 1.84E-08 | 4.72E-08 | 1.22E-07 | 3.14E-07 | 8.09E-07 | 2.09E-06 | 5.38E-06 | 1.39E-05 | 2.27E-05 |
| 2018 | 3.32E-10 | 1.07E-09 | 2.85E-09 | 7.13E-09 | 1.83E-08 | 4.72E-08 | 1.22E-07 | 3.14E-07 | 8.09E-07 | 2.09E-06 | 5.38E-06 | 8.79E-06 |
| 2019 | 1.29E-10 | 4.14E-10 | 1.11E-09 | 2.77E-09 | 7.10E-09 | 1.83E-08 | 4.72E-08 | 1.22E-07 | 3.14E-07 | 8.09E-07 | 2.09E-06 | 3.41E-06 |
| 2020 | 4.99E-11 | 1.61E-10 | 4.29E-10 | 1.07E-09 | 2.75E-09 | 7.10E-09 | 1.83E-08 | 4.72E-08 | 1.22E-07 | 3.14E-07 | 8.09E-07 | 1.32E-06 |

Table 5-6

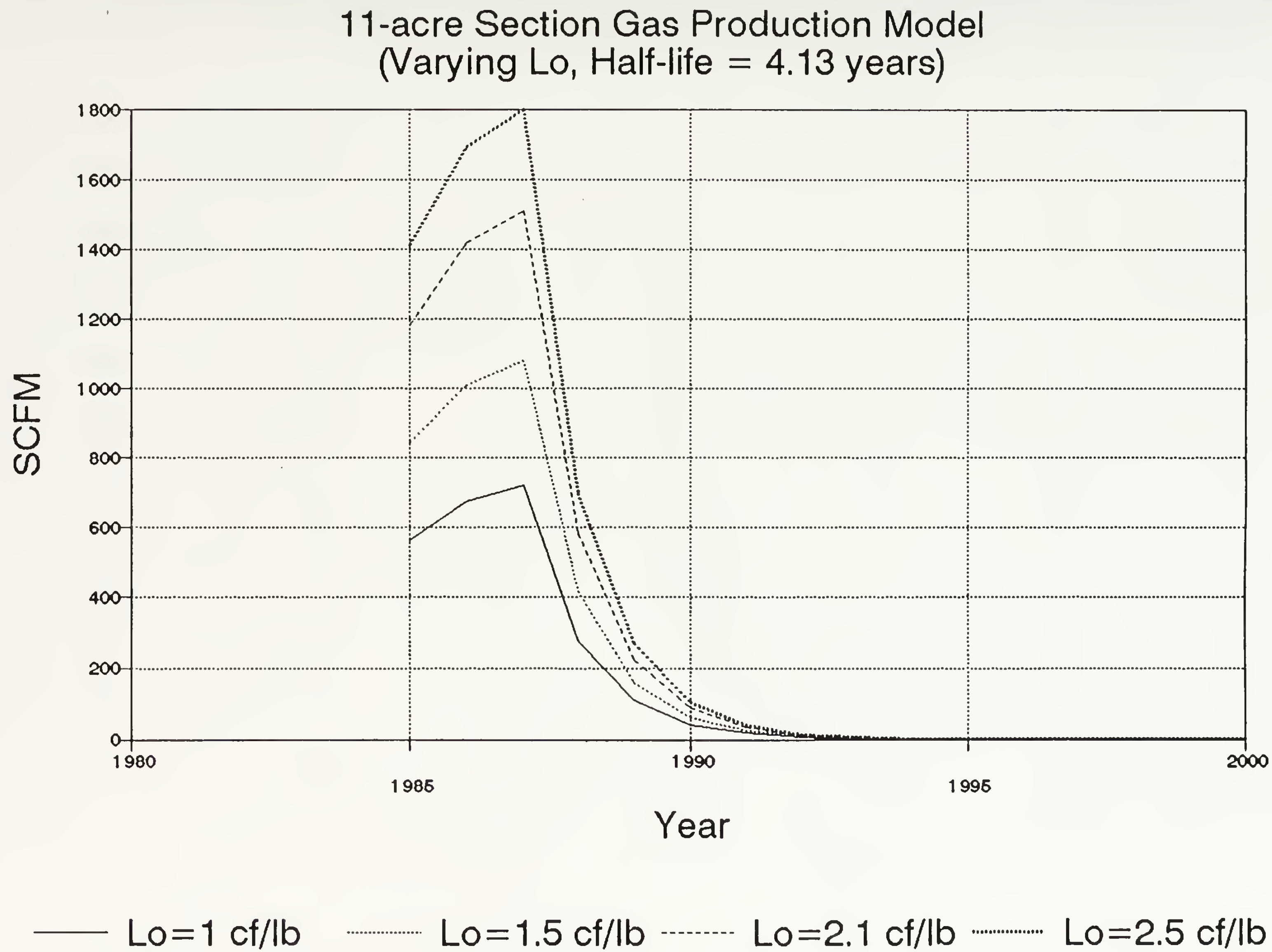


Scholl Canyon Models for ACSWL
(Lo=2.1 cf/lb, Half-life=4.13 years)
SCFM
1800
1600
1400
1200
1000
800
600
400
200
0
1970
1975
1980
1985
1990
1995
2000
2005
Year
30-acre Section
11-acre Section
Active Section


Figure 5-5

recorded, the logical assumptions of $L_o$ and $t_{1/2}$ should give a close representation to the actual gas production assuming there are no limiting factors to the methanogenic activities.

Figures 5-6 through 5-11 show simple manipulations of the Scholl Canyon model to obtain gas production rates for different values of $L_o$ and $t_{1/2}$. With a constant $L_{o,}$ the peak production rate is decreased and the period of production increased as $t_{1/2}$ is increased. As $L_o$ increases with a constant $t_{1/2}$, the total gas production increases while the production period remains unchanged.



11-acre Section Gas Production Model
(Varying Lo, Half-life = 4.13 years)
SCFM
0
200
400
600
800
1000
1200
1400
1600
1800
1980
1985
1990
1995
2000
Year
Lo=1 cf/lb
Lo=1.5 cf/lb
Lo=2.1 cf/lb
Lo=2.5 cf/lb


Figure 5-6

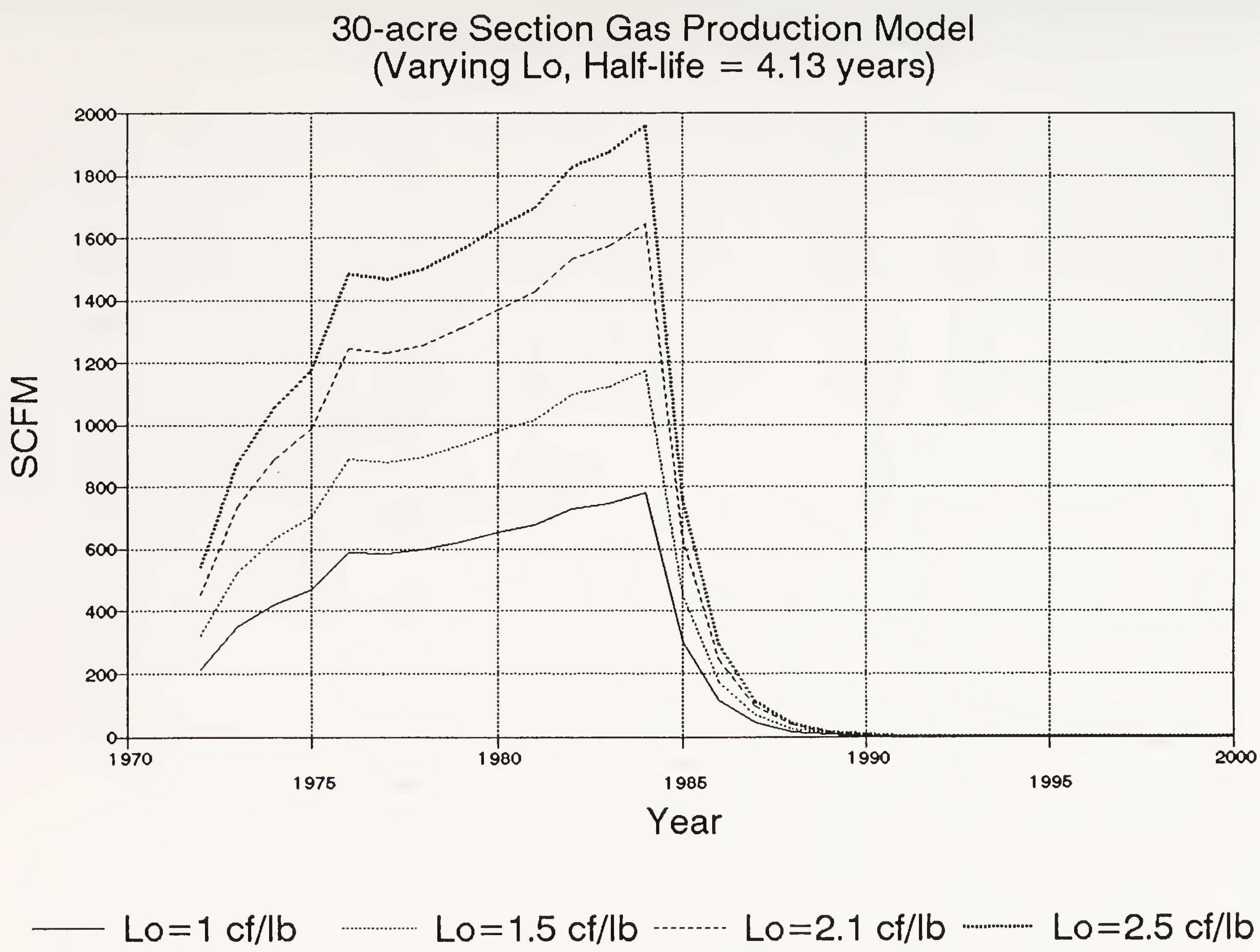
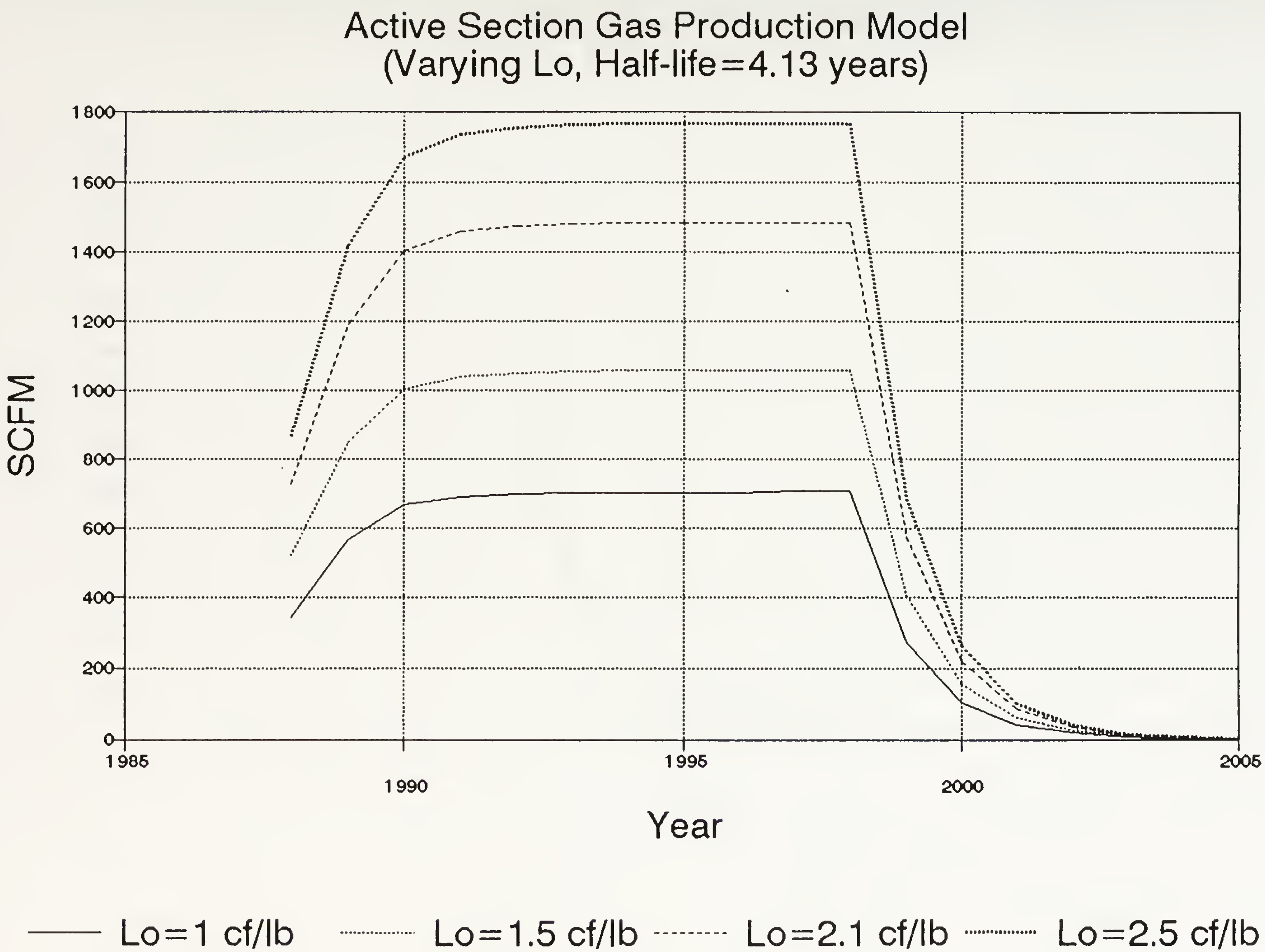

30-acre Section Gas Production Model
(Varying Lo, Half-life = 4.13 years)
SCFM
0
200
400
600
800
1000
1200
1400
1600
1800
2000
1970
1975
1980
1985
1990
1995
2000
Year
Lo=1 cf/lb
Lo=1.5 cf/lb
Lo=2.1 cf/lb
Lo=2.5 cf/lb

Figure 5-7



Active Section Gas Production Model
(Varying Lo, Half-life=4.13 years)
SCFM
1800
1600
1400
1200
1000
800
600
400
200
0
1985
1990
1995
2000
2005
Year
Lo=1 cf/lb
Lo=1.5 cf/lb
Lo=2.1 cf/lb
Lo=2.5 cf/lb


Figure 5-8

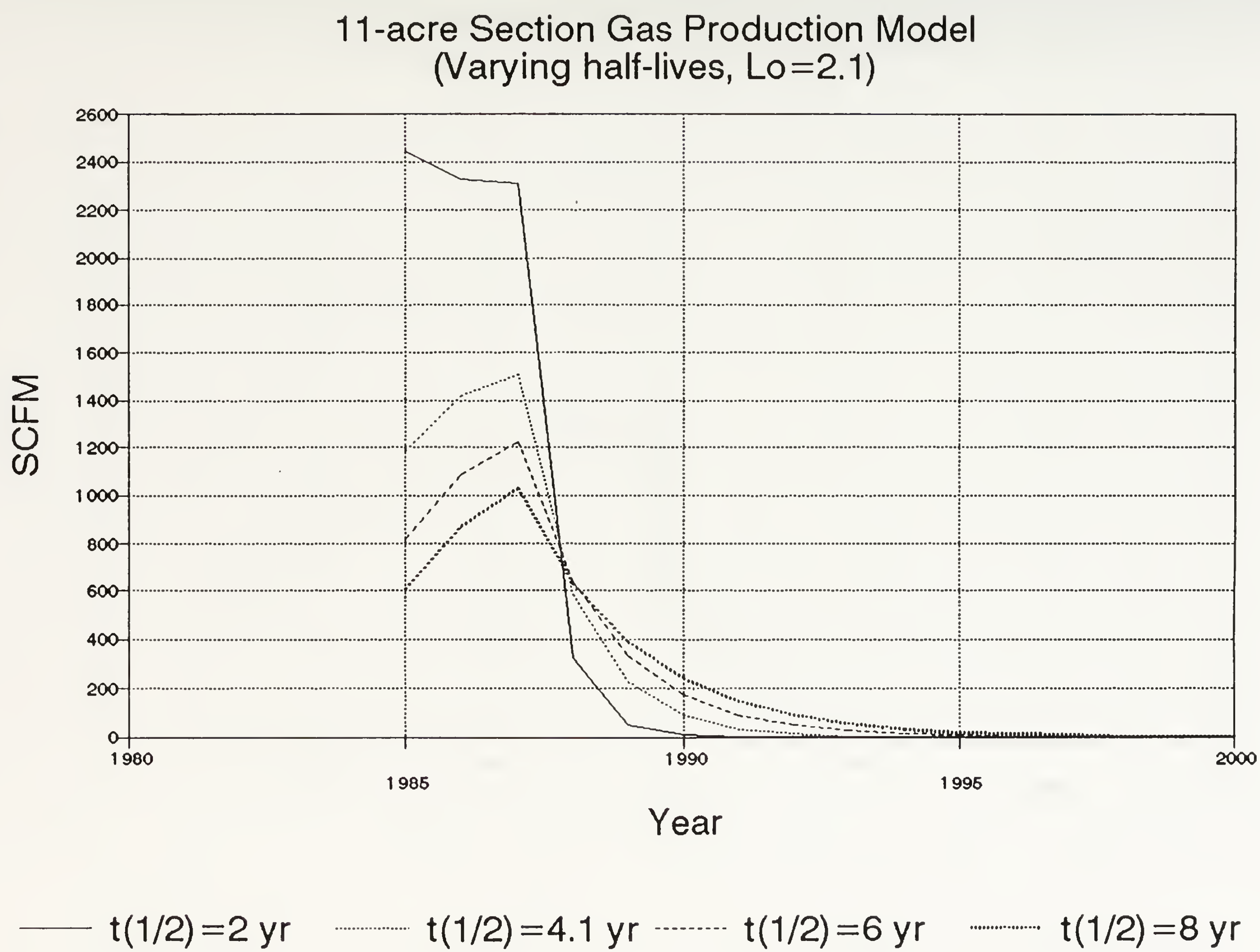

11-acre Section Gas Production Model
(Varying half-lives, Lo=2.1)
SCFM
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1980
1985
1990
1995
2000
Year
t(1/2)=2 yr
t(1/2)=4.1 yr
t(1/2)=6 yr
t(1/2)=8 yr

Figure 5-9

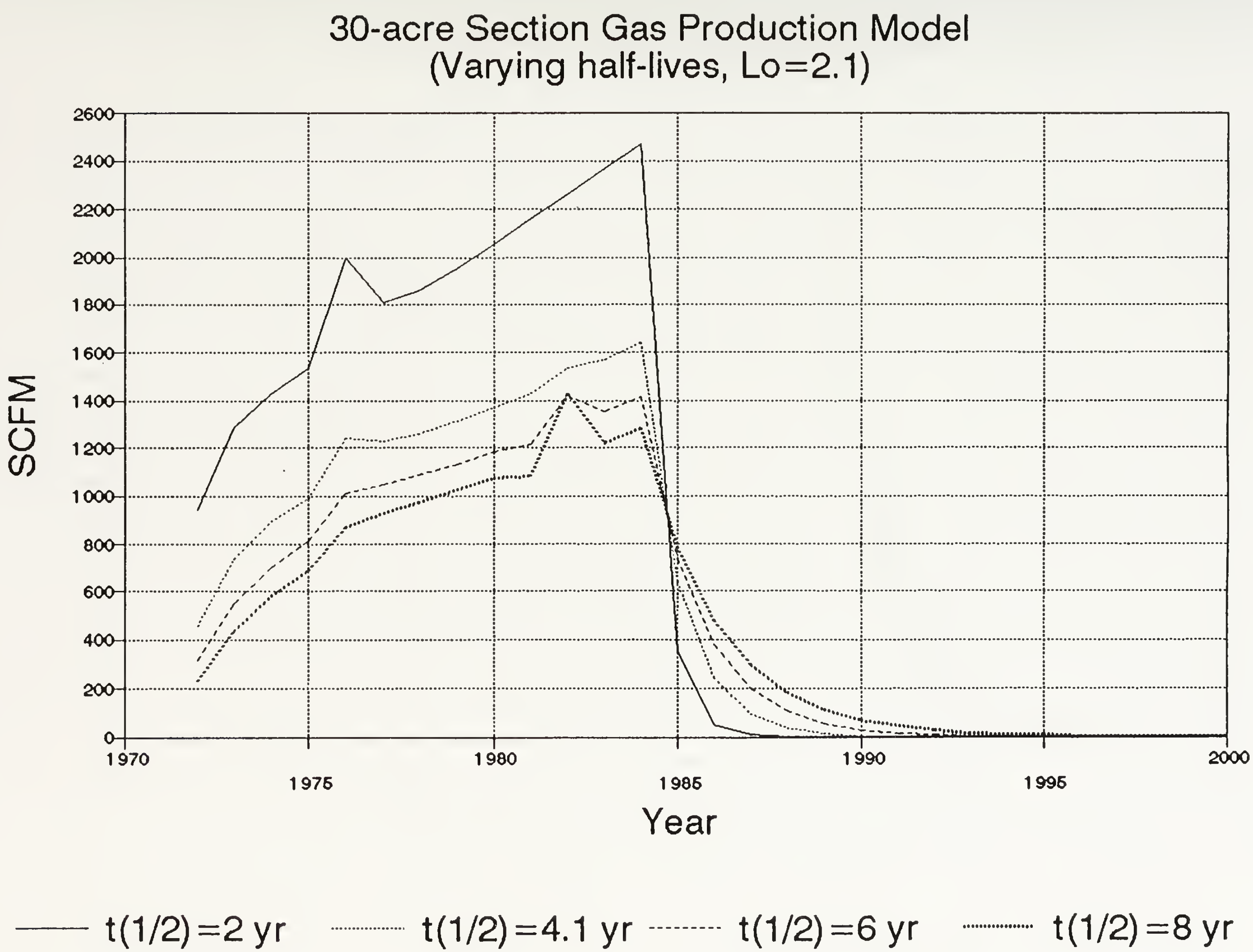

30-acre Section Gas Production Model
(Varying half-lives, Lo=2.1)
SCFM
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1970
1975
1980
1985
1990
1995
2000
Year
t(1/2)=2 yr
t(1/2)=4.1 yr
t(1/2)=6 yr
t(1/2)=8 yr

Figure 5-10

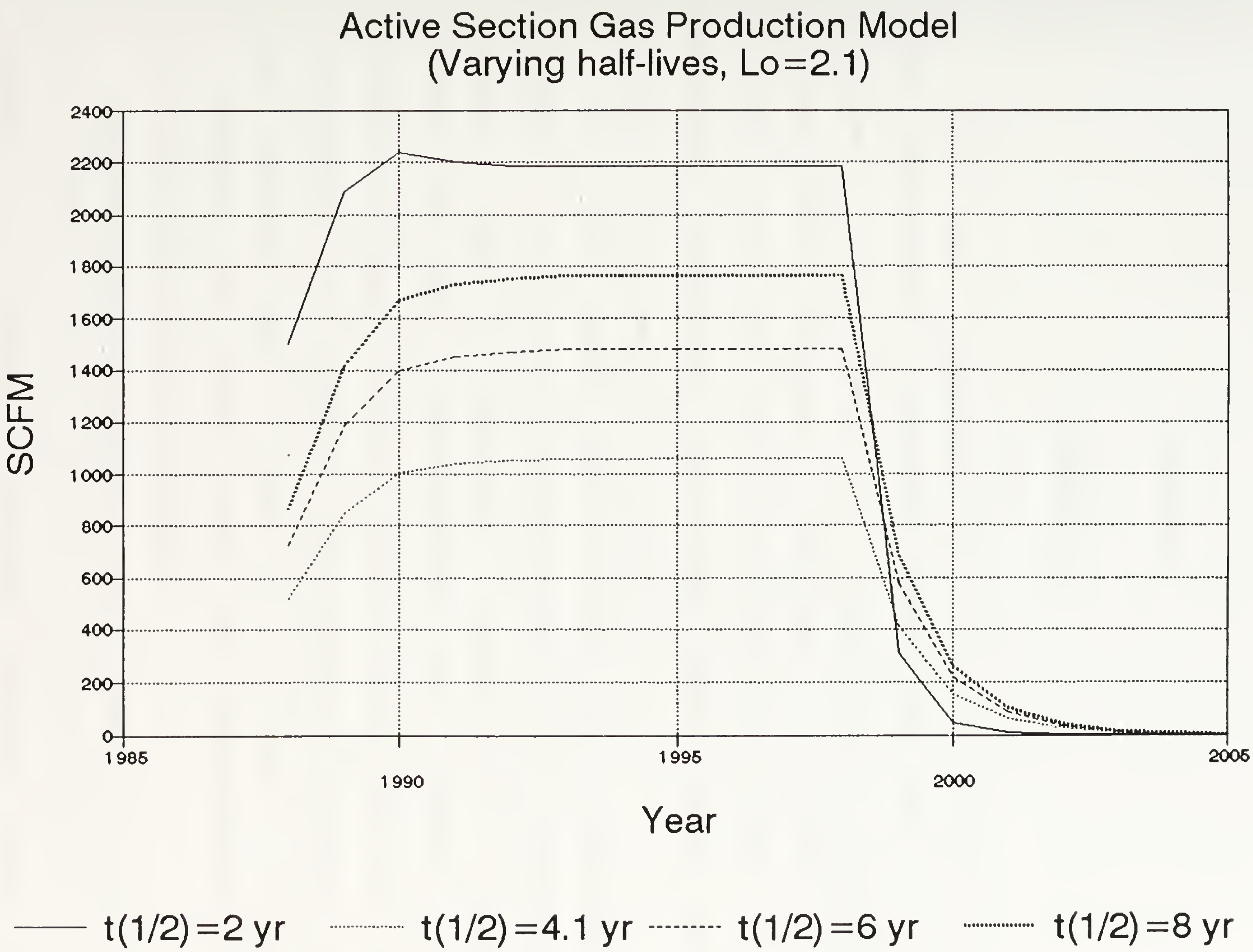

Active Section Gas Production Model
(Varying half-lives, Lo=2.1)
SCFM
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1985
1990
1995
2000
2005
Year
t(1/2)=2 yr
t(1/2)=4.1 yr
t(1/2)=6 yr
t(1/2)=8 yr

Figure 5-11

# CHAPTER 6

# CONCLUSIONS

The period of observation for this report was extremely brief in relation to the total life of the landfill. The measured flows are assumed to be representative "snapshots" of the existing conditions at the ACSWL. As a result, the analysis of the data collected essentially provides for a single point of datum for each landfill section through which the Scholl Canyon model was manipulated.

The Scholl Canyon Model provided for a reasonable assumption of the gas production rates at the ACSWL with respect to time. As discussed in Chapter 5, the ultimate methane production ($L_0$) was calculated to be 2.1 cubic feet of methane per pound of refuse and the refuse half-life was calculated to be 4.13 years. These values are assumed to be representative of the actual conditions and should be utilized as a foundation for further research into LFG generation rates and refuse half-lives at the ACSWL.

The only means of obtaining truly accurate data over an entire landfill, or to allow for reliable projection and modeling, is to install a complete collection system and

conduct field tests to observe the actual maximum volume of gas which can be withdrawn over time. These "point-in-time" measurements provide information that can be used to calibrate selected models such as the Scholl Canyon.

The ACSWL has awarded a contract to install a gas collection system for the purpose of flaring off the LFG. It is suggested that the completed or "full" segments of the active landfill cell should be capped and tied into the proposed ACSWL gas recovery system as soon as operationally feasible. Based upon the assumptions of the Scholl Canyon model, much of the LFG may be lost to the atmosphere soon after the refuse is deposited. Partial capping of the active section and gas extraction will dramatically reduce these losses and will provide for a better analysis of early gas production at the landfill. Continued monitoring of the volume of LFG generated by the ACSWL and its composition is recommended. Additionally, borings and analysis for total solids, total volatile solids, and total organic carbon is desirable to monitor and adjust decay coefficients.

It is fairly well established that methane and carbon dioxide generation rates increase rapidly during the first 3 to 12 months, diminish gradually over the next 5 to 10 years, and the diminish more rapidly during the declining period that may last for an additional 10 to 30 or more years. Evaluation of the data available on landfill gas generation, however, reveals a deficiency of empirical data on basics such as gas

generation rates and total quantity of gas that can be expected per unit quantity of typical solid waste, or on the basis of organic content. Although chemical and physical analytical models of the decomposition process have been developed, knowledge of the maximum quantity of gas generated per unit refuse and the rates at which it is produced are based on theoretical calculations only.

# Appendix A

## Calculation of LFG Properties

Calibration of the rotameter required several calculations with respect to the composite landfill gas. Values for the primary constituent gases that make up the LFG were determined by Dwyer (1992) and are shown in Table 3-1. Assuming an approximate composition of 60% methane and 40% carbon dioxide for a typical sample of ACSWL gas and 1 atm pressure and 40°C, the molecular weight and density was calculated as follows:

### Molecular Weight

$$MW_{LFG}=(\%CH_4)(MW_{CH_4})+(\%CO_2)(MW_{CO_2}) \tag{5}$$

$$MW_{LFG}=(.60)(16.043g/g\text{-}mole)+(.40)(44.01g/g\text{-}mole)$$

$$MW_{LFG}=27.22g/g\text{-}mole$$

### Density

$$\frac{m}{V}=\frac{P(MW)}{RT} \tag{6}$$

$$\frac{m}{V}=\frac{(1atm)(27.22g/g\text{-}mole)}{(0.0821\frac{l\text{-}atm}{g\text{-}mole\text{-}^{o}K})(40+273.15^{o}K)}$$

$$\frac{m}{V}=1.06g/l=0.0662lb/ft^3$$

## Orifice Plate Calculations

Flow and pressure readings were taken on selected landfill vents for the purpose of calibrating the Gilmont rotameter. The data collected is as follows:

| n | Flow (l/min) | Flow (cfm) | $p_1$ (inches $H_2O$) | $p_2$ (inches $H_2O$) |
|---|---|---|---|---|
| 1 | 3 | 0.1059 | 0.15 | 0.00 |
| 2 | 4 | 0.2119 | 0.30 | 0.00 |
| 3 | 8 | 0.2825 | 0.40 | 0.00 |
| 4 | 15 | 0.5297 | 1.00 | 0.05 |
| 5 | 15 | 0.5297 | 1.05 | 0.06 |
| 6 | 17 | 0.6003 | 1.20 | 0.10 |
| 7 | 20 | 0.7062 | 1.60 | 0.20 |

Sakiadis (1984) states that the practical working equation for weight rate of discharge, adopted by A.S.M.E. Research Committee on Fluid Meters, for use with either gases or liquids, is:

$$w = q_1 \rho_1 = KYA_2 \sqrt{2 g_c (p_1 - p_2) \rho_1} \tag{7}$$

where,

$A_2$ = cross-sectional area of the orifice throat ($0.000341\ ft^2$ for a 0.25 inch diameter)
C = coefficient of discharge, dimensionless (0.68 as determined below)
$g_c$ = dimensional constant, 32.17 (lb-ft)/(lb force-$sec^2$)
K = $C/(1-\beta^4)^{0.5}$, dimensionless (0.6805)
$p_1, p_2$ = pressure at upstream and downstream static pressure taps, respectfully, lb force/sq.ft.
$q_1$ = volumetric rate of discharge measured at upstream pressure and temperature, cfs
w = weight rate of discharge, lb/sec
Y = expansion factor, dimensionless (see below)
$\beta$ = ratio of throat diameter to pipe diameter dimensionless (0.25"/1.25" = 0.2)

$\rho_1$ = density at upstream pressure and temperature, lb/cu.ft. (calculated in equation (7) above)

For the flow of gases, expansion factor Y, which allows for the change in gas density as it expands adiabatically from $p_1$ to $p_2$, is given by :

$$Y=1-\frac{1-r}{k}(0.41+0.35\beta^4) \tag{8}$$

where,

r = ratio of downstream to upstream static pressure $p_2/p_1$, dimensionless

k = ratio of specific heats $c_p/c_v$, dimensionless (1.3 as calculated below)

$\beta$ = diameter ratio, dimensionless (0.2)

In order to utilize the above equations, the variables were calculated as follows:

1) Using Table A-1 from Vennard and Street (1975), the nominal value for C was assumed to be 0.61 (This value was later verified against the Reynolds numbers using Figure A-1 as discussed below).

2) The viscosity of the gas mixture was calculated to be $2.8\text{x}10^{-7}$ lb-sec/ft$^2$, or 134.38 $\mu$-poise, using the individual viscosities taken from Weast (1982), see Figure A-2, and incorporating values at 40°C into the following equations from Lily et al. (1984):

$$\mu_{mixture}=\sum_{i=1}^{n}\frac{y_i\mu_i}{\sum_{j=1} y_j\phi_{ij}} \tag{9}$$

where,

n = number of components

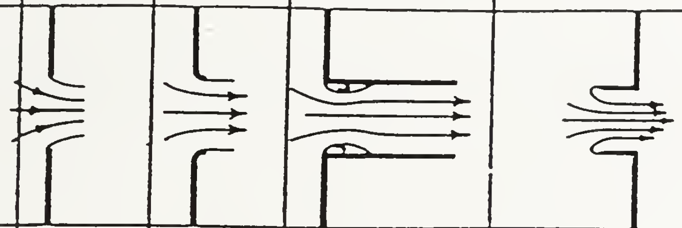
| Orifices and their Nominal Coefficients | | | | |
|---|---|---|---|---|
| | Sharp edged | Rounded | Short tube | Borda |
| |  | | | |
| $C$ | 0.61 | 0.98 | 0.80 | 0.51 |
| $C_c$ | 0.62 | 1.00 | 1.00 | 0.52 |
| $C_v$ | 0.98 | 0.98 | 0.80 | 0.98 |

Table A-1 (Vennard and Street 1975)

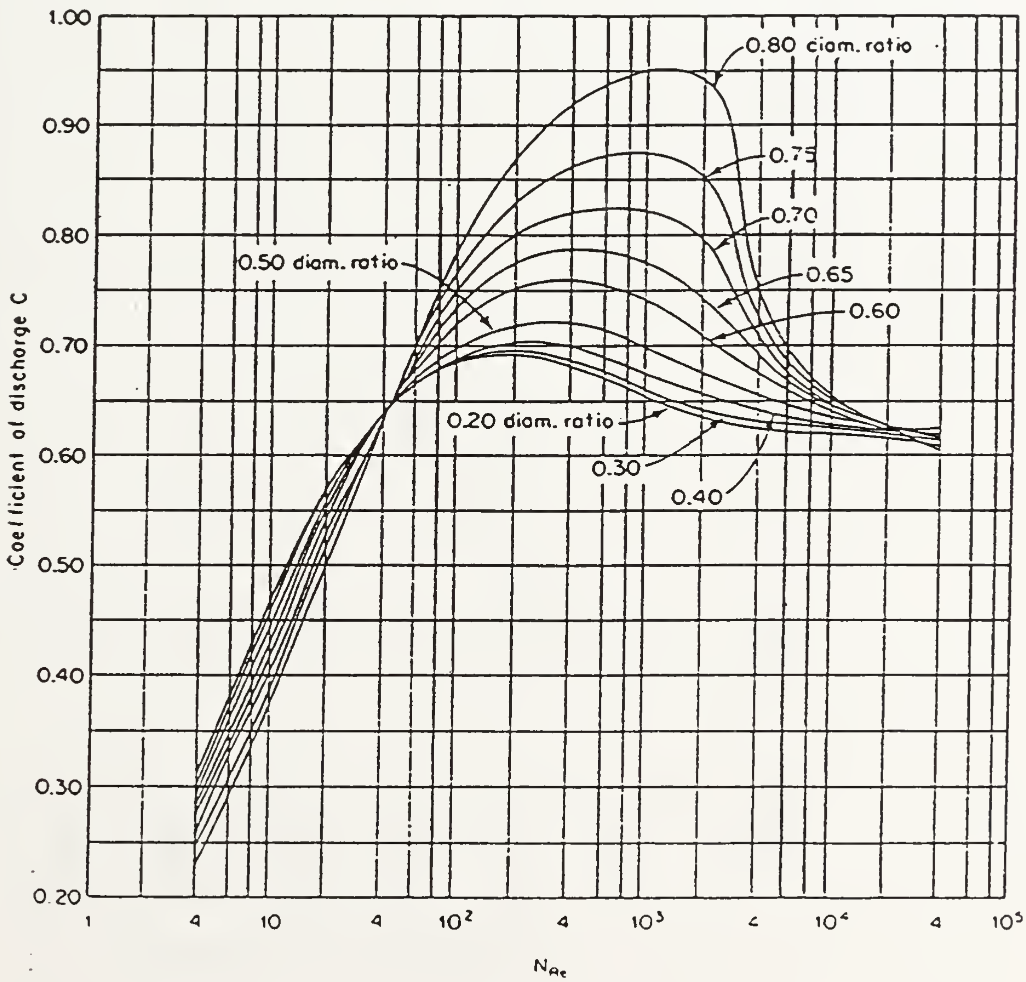



Figure A-1: Coefficient of discharge for square-edged circular orifices (Sakiadis 1984).

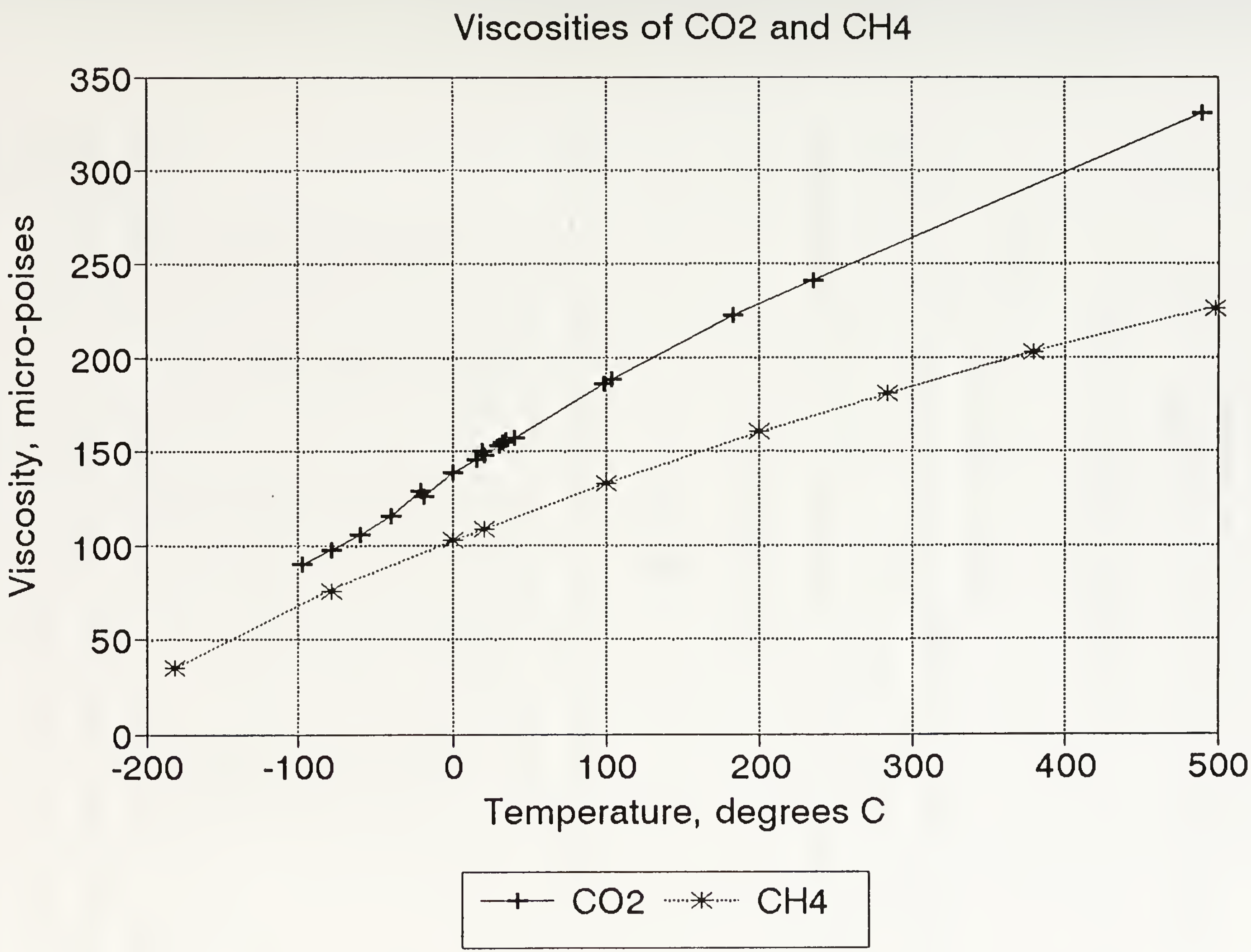

Viscosities of CO2 and CH4
Viscosity, micro-poises
350
300
250
200
150
100
50
0
-200
-100
0
100
200
300
400
500
Temperature, degrees C
CO2
CH4

Figure A-2

$y_i$ = mole fraction
$\mu_i$ = viscosity of pure i at the same temperature
$\phi_{ij}$ = a parameter which may be estimated as shown below,

$$\phi_{ij}=\frac{[1+(\mu_i/\mu_j)^{0.5}(M_j/M_i)^{0.25}]^2}{[8(1+M_i/M_j)]^{0.5}} \tag{10}$$

where,
M = molecular weight

3) The velocity and Reynolds Number were then calculated for the gas flowing through the orifice for each measurement using the equations given by Sakiadis (1984):

$$V=C\sqrt{2\times g_c\times(p_1-p_2)} \tag{11}$$

$$N_{RE}=\frac{Vd\rho}{\mu} \tag{12}$$

The values are presented in the following table:

| n | $p_1$-$p_2$ (inches $H_2O$) | $p_1$-$p_2$ (feet $H_2O$) | V (feet/sec) | $N_{RE}$ |
|---|---|---|---|---|
| 1 | 0.15 | 0.013 | 0.547 | 85.06 |
| 2 | 0.30 | 0.025 | 0.774 | 120.30 |
| 3 | 0.68 | 0.057 | 1.169 | 181.67 |
| 4 | 0.95 | 0.079 | 1.377 | 214.07 |
| 5 | 0.99 | 0.083 | 1.406 | 218.53 |
| 6 | 1.10 | 0.092 | 1.482 | 230.35 |
| 7 | 1.40 | 0.117 | 1.672 | 259.88 |

4) Using the calculated $N_{RE}$, a corrected or "better" value of 0.68 for C was then retrieved from Figure A-1. The velocities and Reynolds numbers were re-calculated as shown below and rechecked with Figure A-1 to verify the revised C value.

| n | $h_2-h_1$ (inches $H_2O$) | $h_2-h_1$ (feet $H_2O$) | V (feet/sec) | $N_{RE}$ |
|---|---|---|---|---|
| 1 | 0.15 | 0.013 | 0.610 | 94.83 |
| 2 | 0.30 | 0.025 | 0.863 | 134.10 |
| 3 | 0.68 | 0.057 | 1.303 | 202.52 |
| 4 | 0.95 | 0.079 | 1.535 | 238.64 |
| 5 | 0.99 | 0.083 | 1.567 | 243.61 |
| 6 | 1.10 | 0.092 | 1.652 | 256.79 |
| 7 | 1.40 | 0.117 | 1.864 | 289.70 |

5) The specific heats for the landfill gas were calculated using the gas constants in Table A-2 and the formulas for heat variation in Table A-3. Both tables are found in Burghardt (1982). A range of calculated values for the specific heats of the primary constituents are shown in Tables A-4 and A-5 and are plotted in Figure A-3. From Burghardt (1982), the specific heats of a mixture may be found by the equations:

$$c_p=\sum_i x_i c_{p_i} \tag{13}$$

$$c_v=\sum_i x_i c_{v_i} \tag{14}$$

where, $x_i$ is the mass fraction and equal to the mass of component i divided by the mass of the mixture. For the mixture, $c_p$ = 2.64 kJ/kg-K, $c_v$ = 2.04 kJ/kg-K, and $c_p/c_v$ = 1.3.

| Gas | $M$ | $c_p$, kJ/kg · K | $c_v$, kJ/kg · K | $k$ | $R$, kJ/kg · K |
|---|---|---|---|---|---|
| Acetylene ($C_2H_2$) | 26.036 | 1.6947 | 1.3753 | 1.232 | 0.3195 |
| Air | 28.97 | 1.0047 | 0.7176 | 1.4 | 0.287 |
| Ammonia ($NH_3$) | 17.032 | 2.089 | 1.5992 | 1.304 | 0.4882 |
| Argon (A) | 39.95 | 0.5208 | 0.3127 | 1.666 | 0.2081 |
| Carbon Dioxide ($CO_2$) | 44.01 | 0.844 | 0.6552 | 1.288 | 0.1889 |
| Carbon Monoxide (CO) | 28.01 | 1.0412 | 0.7444 | 1.399 | 0.2968 |
| Chlorine ($Cl_2$) | 70.914 | 0.4789 | 0.3617 | 1.324 | 0.1172 |
| Ethane ($C_2H_6$) | 30.068 | 1.7525 | 1.4761 | 1.187 | 0.2765 |
| Ethylene ($C_2H_4$) | 28.052 | 1.5297 | 1.2333 | 1.24 | 0.2964 |
| Helium (He) | 4.003 | 5.1954 | 3.1189 | 1.666 | 2.077 |
| Hydrogen ($H_2$) | 2.016 | 14.3136 | 10.190 | 1.4 | 4.125 |
| Hydrazine ($N_2H_4$) | 32.048 | 1.6453 | 1.3815 | 1.195 | 0.2594 |
| Methane ($CH_4$) | 16.043 | 2.1347 | 1.6164 | 1.321 | 0.5183 |
| Neon (Ne) | 20.183 | 1.0298 | 0.6179 | 1.666 | 0.4120 |
| Nitrogen ($N_2$) | 28.016 | 1.0399 | 0.7431 | 1.399 | 0.2968 |
| Oxygen ($O_2$) | 32 | 0.9185 | 0.6585 | 1.395 | 0.2598 |
| Propane ($C_3H_8$) | 44.094 | 1.6683 | 1.4799 | 1.127 | 0.1886 |
| Sulfur Dioxide ($SO_2$) | 64.07 | 0.6225 | 0.4927 | 1.263 | 0.1298 |
| Water Vapor ($H_2O$) | 18.016 | 1.8646 | 1.4033 | 1.329 | 0.4615 |
| Xenon (Xe) | 131.3 | 0.1582 | 0.0950 | 1.666 | 0.0633 |

Table A-2: Gas Constants and Specific Heats at Low Pressures (Burghardt 1982)

| Substance and Temperature Range | $c_p$, kJ/kg·K |
|---|---|
| Air, 280–1500 K | $0.9167 + 2.577 \times 10^{-4}T - 3.974 \times 10^{-8}T^2$ |
| Ammonia, 300–1000 K | $1.5194 + 1.936 \times 10^{-3}T - 1.789 \times 10^{-7}T^2$ |
| Sulfur dioxide, 300–1000 K | $0.7848 + 0.7113 \times 10^{-4}T - 1.73 \times 10^4T^{-2}$ |
| Hydrogen, 300–2200 K | $11.959 + 2.160 \times 10^{-3}T + 30.95T^{-1/2}$ |
| Oxygen, 300–2750 K | $1.507 - 16.77T^{-1/2} + 111.1T^{-1}$ |
| Nitrogen, 300–5000 K | $1.415 - 287.9T^{-1} + 5.35 \times 10^4T^{-2}$ |
| Carbon monoxide, 300–5000 K | $1.415 - 273.3T^{-1} + 4.96 \times 10^4T^{-2}$ |
| $H_2O$, 300–3000 K | $4.613 - 103.3T^{-1/2} + 967.5T^{-1}$ |
| Carbon dioxide, 300–3500 K | $1.540 - 345.1T^{-1} + 4.13 \times 10^4T^{-2}$ |
| Methane, 300–1500 K | $0.8832 + 4.71 \times 10^{-3}T - 1.123 \times 10^{-6}T^2$ |
| Ethylene, 300–1500 K | $0.4039 + 4.35 \times 10^{-3}T - 1.35 \times 10^{-6}T^2$ |
| Ethane, 300–1500 K | $0.306 + 5.34 \times 10^{-3}T - 1.53 \times 10^{-6}T^2$ |
| n-butane ($C_4H_{10}$), 300–1500 K | $0.314 + 5.23 \times 10^{-3}T - 1.60 \times 10^{-6}T^2$ |
| Propane, 300–1500 K | $0.214 + 5.48 \times 10^{-3}T - 1.67 \times 10^{-6}T^2$ |
| Acetylene ($C_2H_2$) 280–1250 K | $1.921 + 7.06 \times 10^{-4}T - 3.73 \times 10^4T^{-2}$ |
| Octane, 225–610 K | $0.290 + 3.97 \times 10^{-3}T$ |

Table A-3: Formulas for Specific Heat Variation with Temperature (Burghardt 1982)

Specific Heat and Specific Heat Ratio Calculations

| Methane | | | | |
|---|---|---|---|---|
| T (C) | Cp (kJ/kg*K) | R (kJ/kg*K) | Cv (kJ/kg*K) | Cp/Cv |
| 27 | 2.1951 | 0.5183 | 1.6768 | 1.3091 |
| 28 | 2.1992 | 0.5183 | 1.6809 | 1.3084 |
| 29 | 2.2032 | 0.5183 | 1.6849 | 1.3076 |
| 30 | 2.2072 | 0.5183 | 1.6889 | 1.3069 |
| 31 | 2.2113 | 0.5183 | 1.6930 | 1.3062 |
| 32 | 2.2153 | 0.5183 | 1.6970 | 1.3054 |
| 33 | 2.2193 | 0.5183 | 1.7010 | 1.3047 |
| 34 | 2.2233 | 0.5183 | 1.7050 | 1.3040 |
| 35 | 2.2273 | 0.5183 | 1.7090 | 1.3033 |
| 36 | 2.2314 | 0.5183 | 1.7131 | 1.3026 |
| 37 | 2.2354 | 0.5183 | 1.7171 | 1.3018 |
| 38 | 2.2394 | 0.5183 | 1.7211 | 1.3011 |
| 39 | 2.2434 | 0.5183 | 1.7251 | 1.3004 |
| 40 | 2.2474 | 0.5183 | 1.7291 | 1.2997 |
| 41 | 2.2514 | 0.5183 | 1.7331 | 1.2991 |
| 42 | 2.2554 | 0.5183 | 1.7371 | 1.2984 |
| 43 | 2.2594 | 0.5183 | 1.7411 | 1.2977 |
| 44 | 2.2634 | 0.5183 | 1.7451 | 1.2970 |
| 45 | 2.2674 | 0.5183 | 1.7491 | 1.2963 |
| 46 | 2.2714 | 0.5183 | 1.7531 | 1.2956 |
| 47 | 2.2754 | 0.5183 | 1.7571 | 1.2950 |
| 48 | 2.2794 | 0.5183 | 1.7611 | 1.2943 |
| 49 | 2.2834 | 0.5183 | 1.7651 | 1.2936 |
| 50 | 2.2874 | 0.5183 | 1.7691 | 1.2930 |

Table A-4

Specific Heat and Specific Heat Ratio Calculations

| Carbon dioxide | | | | |
|---|---|---|---|---|
| T (C) | Cp (kJ/kg*K) | R (kJ/kg*K) | Cv (kJ/kg*K) | Cp/Cv |
| 27 | 0.8486 | 0.1889 | 0.6597 | 1.2864 |
| 28 | 0.8493 | 0.1889 | 0.6604 | 1.2860 |
| 29 | 0.8501 | 0.1889 | 0.6612 | 1.2857 |
| 30 | 0.8509 | 0.1889 | 0.6620 | 1.2853 |
| 31 | 0.8517 | 0.1889 | 0.6628 | 1.2850 |
| 32 | 0.8525 | 0.1889 | 0.6636 | 1.2847 |
| 33 | 0.8533 | 0.1889 | 0.6644 | 1.2843 |
| 34 | 0.8541 | 0.1889 | 0.6652 | 1.2840 |
| 35 | 0.8549 | 0.1889 | 0.6660 | 1.2836 |
| 36 | 0.8557 | 0.1889 | 0.6668 | 1.2833 |
| 37 | 0.8565 | 0.1889 | 0.6676 | 1.2829 |
| 38 | 0.8574 | 0.1889 | 0.6685 | 1.2826 |
| 39 | 0.8582 | 0.1889 | 0.6693 | 1.2822 |
| 40 | 0.8590 | 0.1889 | 0.6701 | 1.2819 |
| 41 | 0.8598 | 0.1889 | 0.6709 | 1.2815 |
| 42 | 0.8607 | 0.1889 | 0.6718 | 1.2812 |
| 43 | 0.8615 | 0.1889 | 0.6726 | 1.2808 |
| 44 | 0.8623 | 0.1889 | 0.6734 | 1.2805 |
| 45 | 0.8632 | 0.1889 | 0.6743 | 1.2801 |
| 46 | 0.8640 | 0.1889 | 0.6751 | 1.2798 |
| 47 | 0.8649 | 0.1889 | 0.6760 | 1.2794 |
| 48 | 0.8657 | 0.1889 | 0.6768 | 1.2791 |
| 49 | 0.8666 | 0.1889 | 0.6777 | 1.2787 |
| 50 | 0.8674 | 0.1889 | 0.6785 | 1.2784 |

Table A-5

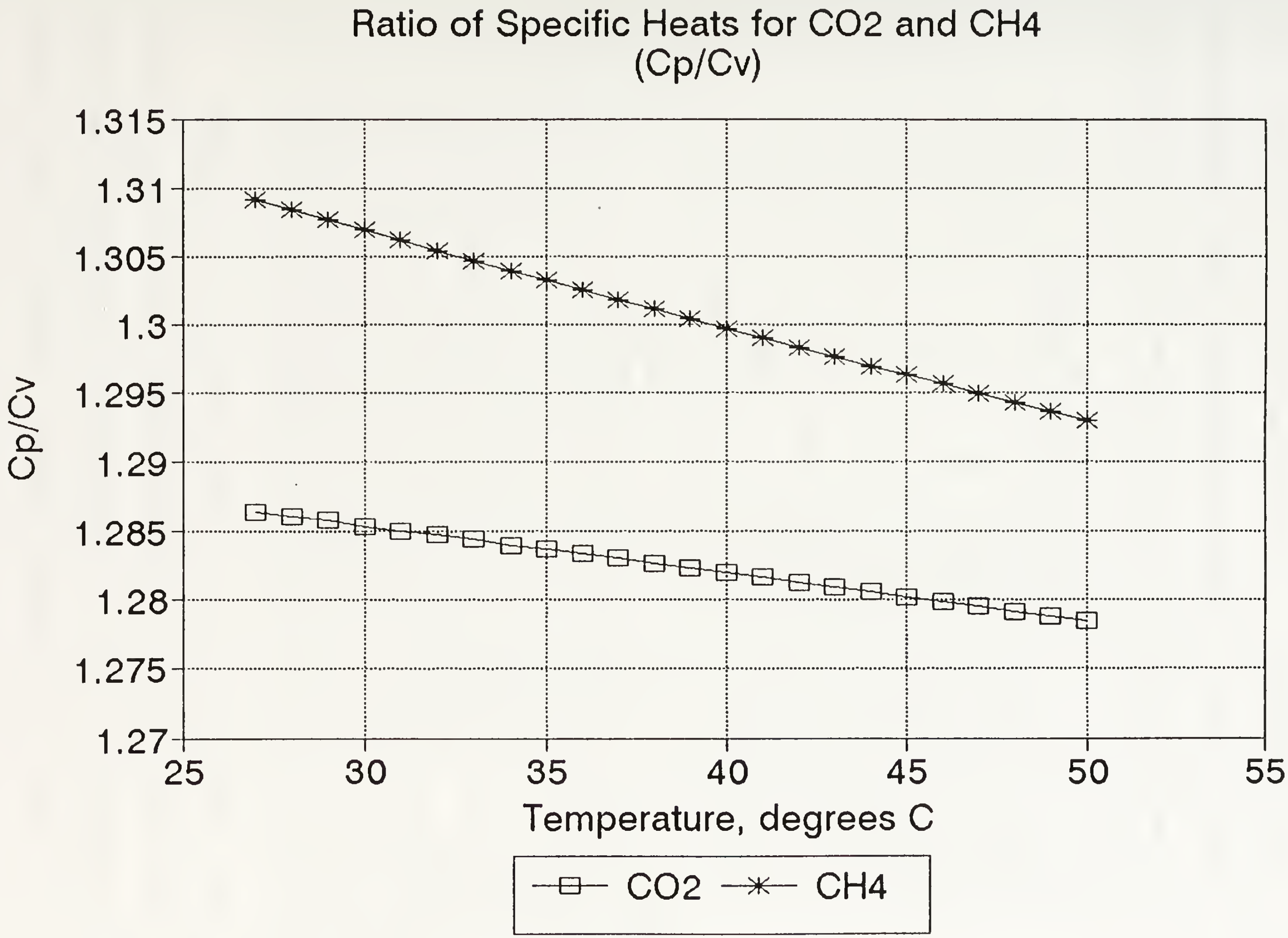

Ratio of Specific Heats for CO2 and CH4
(Cp/Cv)
Cp/Cv
1.315
1.31
1.305
1.3
1.295
1.29
1.285
1.28
1.275
1.27
25
30
35
40
45
50
55
Temperature, degrees C
CO2
CH4

Figure A-3

With the revised coefficient of discharge, equations (7) and (8) were then solved for their respective flow values. Calculations and supporting data for the orifice plate calibration are presented in the following tables:

| n | $p_1-p_2$ (inches $H_2O$) | $p_1-p_2$ (ft $H_2O$) | r | 1-r |
|---|---|---|---|---|
| 1 | 0.15 | 0.0125 | 0.000 | 1.000 |
| 2 | 0.30 | 0.0250 | 0.000 | 1.000 |
| 3 | 0.40 | 0.0333 | 0.000 | 1.000 |
| 4 | 0.95 | 0.0792 | 0.050 | 0.950 |
| 5 | 0.99 | 0.0825 | 0.057 | 0.943 |
| 6 | 1.10 | 0.0917 | 0.083 | 0.917 |
| 7 | 1.40 | 0.1167 | 0.125 | 0.875 |

| n | Y | $q_1*\rho$ (lb/sec) | Q (cfs) | Q (l/min) | Q (l/min) [regressed] |
|---|---|---|---|---|---|
| 1 | 0.6842 | 6.52E-06 | 0.0031 | 5.2861 | 5.3057 |
| 2 | 0.6842 | 9.21E-06 | 0.0044 | 7.4757 | 7.3890 |
| 3 | 0.6842 | 10.64E-06 | 0.0051 | 8.6322 | 8.7779 |
| 4 | 0.7000 | 16.78E-06 | 0.0080 | 13.6102 | 13.6390 |
| 5 | 0.7022 | 17.19E-06 | 0.0082 | 13.9386 | 13.6390 |
| 6 | 0.7105 | 18.33E-06 | 0.0087 | 14.8656 | 15.0279 |
| 7 | 0.7237 | 21.06E-06 | 0.0101 | 17.0813 | 17.1112 |

Figure A-4 is the regressed calibration curve. Corrected values for the flow rates measured in the field were then obtained utilizing the equation for the calibration curve. These corrected values are also presented in Appendix B.

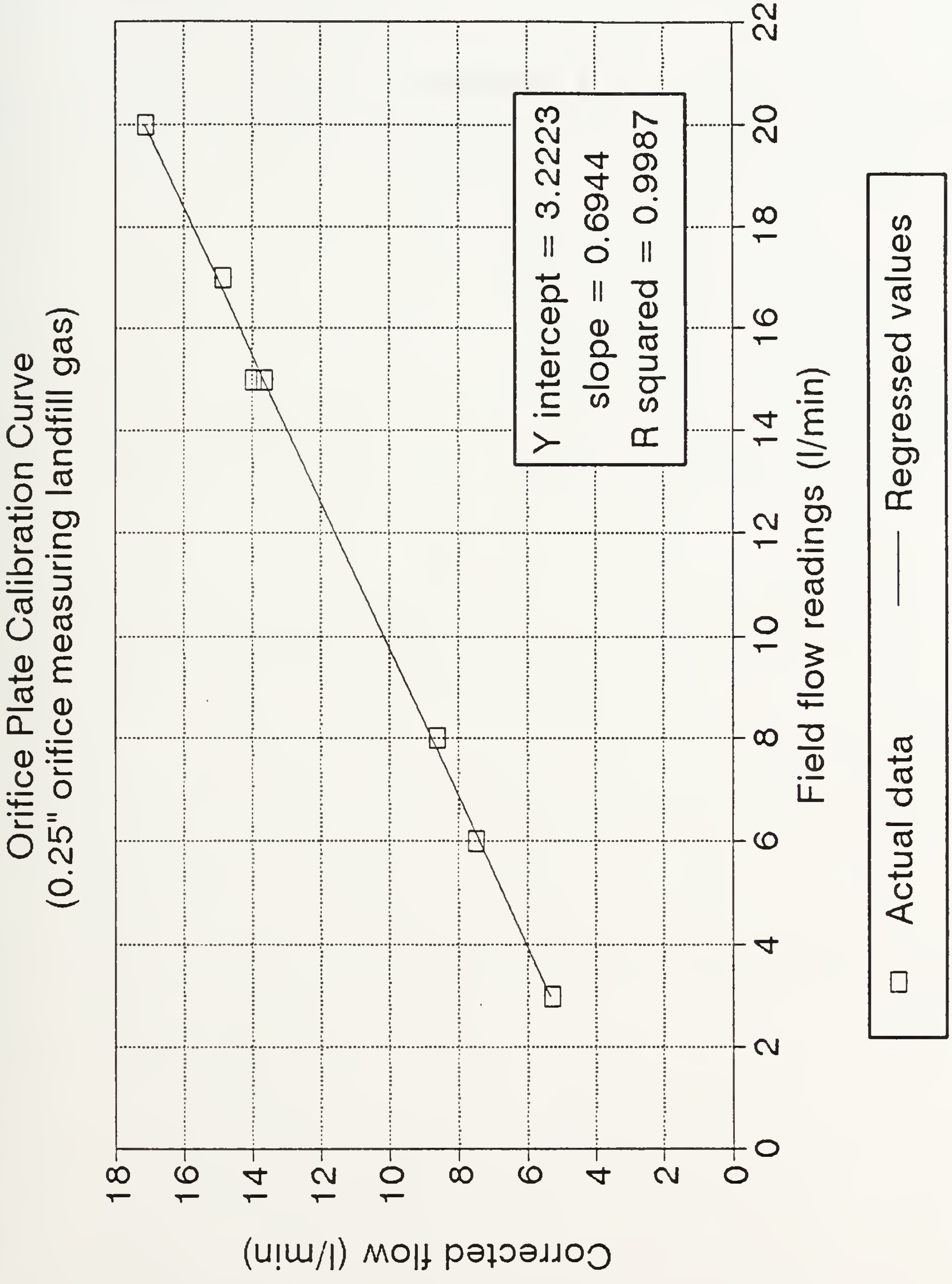

Orifice Plate Calibration Curve
(0.25" orifice measuring landfill gas)
Corrected flow (l/min)
Field flow readings (l/min)
0
2
4
6
8
10
12
14
16
18
20
22
Y intercept = 3.2223
slope = 0.6944
R squared = 0.9987
Actual data
Regressed values

Figure A-4

Appendix B

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 19-Jul-91 | 1 | 1 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 24-Jul-91 | 6 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 29-Jul-91 | 11 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 02-Aug-91 | 15 | | BDL | BDL | BDL | BDL | | 0.05 | 0.02 |
| 07-Aug-91 | 20 | | BDL | BDL | BDL | BDL | | 0.02 | 0.02 |
| 09-Aug-91 | 22 | | BDL | BDL | BDL | BDL | | 0.05 | 0.00 |
| 24-Aug-91 | 37 | | BDL | BDL | BDL | BDL | | 0.20 | 0.15 |
| 29-Aug-91 | 42 | | BDL | BDL | BDL | BDL | | 0.20 | 0.20 |
| 07-Sep-91 | 51 | | BDL | BDL | BDL | BDL | | 0.25 | 0.25 |
| 11-Sep-91 | 55 | | BDL | BDL | BDL | BDL | | 0.20 | 0.20 |
| 12-Oct-91 | 86 | | BDL | BDL | BDL | BDL | | 0.50 | 0.40 |
| 23-Oct-91 | 97 | | BDL | BDL | BDL | BDL | | 0.50 | 0.45 |
| 08-Jan-92 | 174 | | BDL | BDL | BDL | BDL | | 0.40 | 0.40 |
| 22-Jan-92 | 188 | | BDL | BDL | BDL | BDL | | 0.50 | 0.50 |
| 11-Feb-92 | 208 | | BDL | BDL | BDL | BDL | | 0.50 | 0.30 |
| 19-Jul-91 | 1 | 2 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 29-Jul-91 | 11 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 29-Jul-91 | 11 | | BDL | BDL | BDL | BDL | | 0.55 | 0.15 |
| 02-Aug-91 | 15 | | BDL | BDL | BDL | BDL | | 0.25 | 0.08 |
| 07-Aug-91 | 20 | | BDL | BDL | BDL | BDL | | 0.10 | 0.10 |
| 09-Aug-91 | 22 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 24-Aug-91 | 37 | | BDL | BDL | BDL | BDL | | 0.05 | 0.05 |
| 29-Aug-91 | 42 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 07-Sep-91 | 51 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 11-Sep-91 | 55 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 12-Oct-91 | 86 | | BDL | BDL | BDL | BDL | | 0.05 | 0.00 |
| 23-Oct-91 | 97 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 08-Jan-92 | 174 | | BDL | BDL | BDL | BDL | | 0.10 | 0.10 |
| 22-Jan-92 | 188 | | BDL | BDL | BDL | BDL | | 0.20 | 0.20 |
| 11-Feb-92 | 208 | | BDL | BDL | BDL | BDL | | 0.30 | 0.20 |

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 24-Jul-91 | 1 | 3 | 49.50 | 37.60 | 1.33 | 0.7987 | 0.64 | 19.30 | 17.40 |
| 29-Jul-91 | 6 | | 52.00 | 39.33 | 1.39 | 0.8379 | | 20.30 | 18.55 |
| 24-Aug-91 | 32 | | 52.00 | 39.33 | 1.39 | 0.8203 | | 12.40 | 9.65 |
| 31-Aug-91 | 39 | | 39.00 | 30.30 | 1.07 | 0.6358 | | 13.50 | 12.10 |
| 07-Sep-91 | 46 | | 35.00 | 27.53 | 0.97 | 0.5767 | | 12.40 | 11.50 |
| 11-Sep-91 | 50 | | 27.50 | 22.32 | 0.79 | 0.4643 | | 12.50 | 8.60 |
| 12-Oct-91 | 81 | | 41.00 | 31.69 | 1.12 | 0.6662 | | 20.20 | 12.90 |
| 17-Oct-91 | 86 | | 39.00 | 30.30 | 1.07 | 0.6373 | | 20.50 | 13.10 |
| 23-Oct-91 | 92 | | 37.00 | 28.92 | 1.02 | 0.6062 | | 20.05 | 11.80 |
| 08-Jan-92 | 169 | | 30.00 | 24.06 | 0.85 | 0.5002 | | 8.40 | 8.40 |
| 22-Jan-92 | 183 | | 30.00 | 24.06 | 0.85 | 0.5000 | | 14.00 | 8.20 |
| 11-Feb-92 | 203 | | 41.00 | 31.69 | 1.12 | 0.6687 | | 24.50 | 14.50 |
| 24-Jul-91 | 1 | 4 | 28.00 | 22.67 | 0.80 | 0.4714 | 0.52 | 9.50 | 8.45 |
| 29-Jul-91 | 6 | | 39.00 | 30.30 | 1.07 | 0.6370 | | 13.60 | 12.90 |
| 24-Aug-91 | 32 | | 30.50 | 24.40 | 0.86 | 0.5084 | | 10.70 | 9.20 |
| 31-Aug-91 | 39 | | 38.00 | 29.61 | 1.05 | 0.6205 | | 12.60 | 11.60 |
| 07-Sep-91 | 46 | | 34.00 | 26.83 | 0.95 | 0.5609 | | 12.00 | 10.60 |
| 11-Sep-91 | 50 | | 33.00 | 26.14 | 0.92 | 0.5459 | | 11.20 | 10.20 |
| 12-Oct-91 | 81 | | 37.00 | 28.92 | 1.02 | 0.6058 | | 12.60 | 11.50 |
| 26-Dec-91 | 156 | | 20.00 | 17.11 | 0.60 | 0.3530 | | 5.30 | 5.10 |
| 11-Feb-92 | 203 | | 20.77 | 17.65 | 0.62 | 0.3642 | | 6.50 | 5.30 |
| 08-Jan-92 | 1 | 6 | 11.00 | 10.86 | 0.38 | 0.2227 | 0.24 | 2.80 | 2.60 |
| 22-Jan-92 | 15 | | 12.00 | 11.56 | 0.41 | 0.2370 | | 2.90 | 2.70 |
| 11-Feb-92 | 35 | | 13.00 | 12.25 | 0.43 | 0.2516 | | 3.70 | 3.30 |
| 08-Jan-92 | 1 | 8 | BDL | BDL | BDL | BDL | 0.00 | 0.20 | 0.20 |
| 22-Jan-92 | 15 | | BDL | BDL | BDL | BDL | | 0.30 | 0.30 |
| 11-Feb-92 | 35 | | BDL | BDL | BDL | BDL | | 0.80 | 0.70 |

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 12-Jul-91 | 1 | I1 | 21.55 | 18.19 | 0.64 | 0.3753 | 0.37 | 8.40 | 5.20 |
| 14-Aug-91 | 34 | | 21.00 | 17.81 | 0.63 | 0.3679 | | 7.20 | 5.75 |
| 12-Oct-91 | 93 | | 21.00 | 17.81 | 0.63 | 0.3678 | | 7.10 | 5.60 |
| 27-Dec-91 | 169 | | 21.00 | 17.81 | 0.63 | 0.3664 | | 5.30 | 4.10 |
| 12-Jul-91 | 1 | I2 | 19.00 | 16.42 | 0.58 | 0.3381 | 0.32 | 6.60 | 4.45 |
| 14-Aug-91 | 34 | | 17.00 | 15.03 | 0.53 | 0.3093 | | 5.40 | 4.20 |
| 12-Oct-91 | 93 | | 17.00 | 15.03 | 0.53 | 0.3094 | | 5.60 | 4.30 |
| 27-Dec-91 | 169 | | 19.00 | 16.42 | 0.58 | 0.3377 | | 4.80 | 3.90 |
| 07-Aug-91 | 1 | I3 | 17.50 | 15.38 | 0.54 | 0.3165 | 0.32 | 4.70 | 4.20 |
| 17-Oct-91 | 72 | | 17.00 | 15.00 | 0.53 | 0.3088 | | | 4.30 |
| 27-Dec-91 | 143 | | 19.00 | 16.42 | 0.58 | 0.3377 | | 4.30 | 3.90 |
| 07-Aug-91 | 1 | I4 | BDL | BDL | BDL | BDL | 0.00 | 0.01 | 0.01 |
| 17-Oct-91 | 72 | | BDL | BDL | BDL | BDL | | | 0.02 |
| 27-Dec-91 | 143 | | BDL | BDL | BDL | BDL | | 0.30 | 0.02 |
| 07-Aug-91 | 1 | I5 | 33.00 | 26.14 | 0.92 | 0.5463 | 0.51 | 11.70 | 10.50 |
| 17-Oct-91 | 72 | | 29.00 | 23.36 | 0.83 | 0.4872 | | 10.20 | 9.60 |
| 27-Dec-91 | 143 | | 30.00 | 24.06 | 0.85 | 0.4995 | | 9.30 | 7.80 |
| 07-Aug-91 | 1 | I6 | 22.00 | 18.50 | 0.65 | 0.3821 | 0.34 | 6.40 | 5.60 |
| 17-Oct-91 | 72 | | 18.00 | 15.72 | 0.56 | 0.3227 | | 4.80 | 3.00 |
| 27-Dec-91 | 143 | | 18.00 | 15.72 | 0.56 | 0.3231 | | 4.00 | 3.50 |
| 02-Aug-91 | 1 | I7 | 18.50 | 16.07 | 0.57 | 0.3312 | 0.32 | 5.20 | 4.70 |
| 23-Oct-91 | 83 | | 17.00 | 15.03 | 0.53 | 0.3093 | | 4.40 | 4.20 |
| 27-Dec-91 | 148 | | 18.00 | 15.72 | 0.56 | 0.3231 | | 4.80 | 3.50 |
| 02-Aug-91 | 1 | I8 | 34.00 | 26.83 | 0.95 | 0.5625 | 0.56 | 14.40 | 11.80 |
| 23-Oct-91 | 83 | | 34.00 | 26.83 | 0.95 | 0.5604 | | 12.20 | 10.20 |
| 27-Dec-91 | 148 | | 33.00 | 26.14 | 0.92 | 0.5452 | | 11.50 | 9.70 |

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 02-Aug-91 | 1 | 110 | 46.00 | 35.17 | 1.24 | 0.7445 | 0.67 | 20.40 | 15.90 |
| 23-Oct-91 | 83 | | 41.00 | 31.69 | 1.12 | 0.6671 | | 18.50 | 13.50 |
| 27-Dec-91 | 148 | | 37.00 | 28.92 | 1.02 | 0.6066 | | 16.40 | 12.10 |
| 02-Aug-91 | 1 | 111 | 22.00 | 18.50 | 0.65 | 0.3821 | 0.40 | 6.20 | 5.60 |
| 23-Oct-91 | 83 | | 23.00 | 19.19 | 0.68 | 0.3968 | | 7.00 | 6.00 |
| 27-Dec-91 | 148 | | 25.00 | 20.58 | 0.73 | 0.4250 | | 6.50 | 5.50 |
| 02-Aug-91 | 1 | 112 | 22.00 | 18.50 | 0.65 | 0.3825 | 0.41 | 6.75 | 6.05 |
| 17-Oct-91 | 77 | | 26.00 | 21.28 | 0.75 | 0.4386 | | 5.50 | 4.80 |
| 27-Dec-91 | 148 | | 23.00 | 19.19 | 0.68 | 0.3960 | | 5.50 | 5.10 |
| 02-Aug-91 | 1 | 113 | 41.00 | 31.69 | 1.12 | 0.6675 | 0.61 | 17.35 | 13.70 |
| 17-Oct-91 | 77 | | 35.00 | 27.53 | 0.97 | 0.5776 | | 14.10 | 12.20 |
| 27-Dec-91 | 148 | | 35.00 | 27.53 | 0.97 | 0.5750 | | 11.90 | 10.30 |
| 29-Jul-91 | 1 | 114 | 16.00 | 14.33 | 0.51 | 0.2945 | 0.24 | 3.95 | 3.50 |
| 17-Oct-91 | 81 | | 12.00 | 11.56 | 0.41 | 0.2368 | | 2.50 | 2.30 |
| 27-Dec-91 | 152 | | 8.00 | 8.78 | 0.31 | 0.1796 | | 2.00 | 1.80 |
| 29-Jul-91 | 1 | 115 | 15.00 | 13.64 | 0.48 | 0.2801 | 0.24 | 3.70 | 3.25 |
| 11-Sep-91 | 45 | | 15.00 | 13.64 | 0.48 | 0.2797 | | 2.95 | 2.65 |
| 27-Dec-91 | 152 | | 7.00 | 8.08 | 0.29 | 0.1654 | | 1.80 | 1.70 |
| 24-Jul-91 | 1 | 116 | 8.00 | 8.78 | 0.31 | 0.1798 | 0.22 | 2.95 | 2.20 |
| 29-Jul-91 | 6 | | 14.00 | 12.94 | 0.46 | 0.2657 | | 3.20 | 3.05 |
| 11-Sep-91 | 50 | | 13.00 | 12.25 | 0.43 | 0.2509 | | 3.20 | 2.20 |
| 27-Dec-91 | 157 | | 8.00 | 8.78 | 0.31 | 0.1796 | | 2.40 | 1.80 |

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 10-Jul-91 | 1 | GV1 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 12-Oct-91 | 95 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 27-Dec-91 | 171 | | BDL | BDL | BDL | BDL | | 0.10 | 0.10 |
| 10-Jul-91 | 1 | GV2 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 12-Oct-91 | 95 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 27-Dec-91 | 171 | | BDL | BDL | BDL | BDL | | 0.10 | 0.10 |
| 10-Jul-91 | 1 | GV3 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 12-Oct-91 | 95 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 27-Dec-91 | 171 | | BDL | BDL | BDL | BDL | | 0.30 | 0.30 |
| 10-Jul-91 | 1 | GV4 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 12-Oct-91 | 95 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 27-Dec-91 | 171 | | BDL | BDL | BDL | BDL | | 0.40 | 0.30 |
| 10-Jul-91 | 1 | GV5 | BDL | BDL | BDL | BDL | 0.00 | 0.20 | 0.00 |
| 12-Oct-91 | 95 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 27-Dec-91 | 171 | | BDL | BDL | BDL | BDL | | 0.60 | 0.00 |
| 10-Jul-91 | 1 | GV6 | 4.00 | 6.00 | 0.21 | 0.1225 | 0.14 | 0.85 | 0.65 |
| 12-Oct-91 | 95 | | 7.00 | 8.08 | 0.29 | 0.1651 | | 1.20 | 1.00 |
| 27-Dec-91 | 171 | | 4.00 | 6.00 | 0.21 | 0.1225 | | 0.90 | 0.70 |
| 10-Jul-91 | 1 | GV7 | 8.00 | 8.78 | 0.31 | 0.1799 | 0.18 | 2.40 | 2.30 |
| 12-Oct-91 | 95 | | 9.00 | 9.47 | 0.33 | 0.1940 | | 2.50 | 2.20 |
| 27-Dec-91 | 171 | | 8.00 | 8.78 | 0.31 | 0.1799 | | 2.30 | 2.30 |
| 31-Aug-91 | 1 | GV8 | 4.00 | 6.00 | 0.21 | 0.1226 | 0.13 | 1.30 | 1.15 |
| 17-Oct-91 | 48 | | 4.00 | 6.00 | 0.21 | 0.1224 | | 0.50 | 0.40 |
| 27-Dec-91 | 119 | | 5.00 | 6.70 | 0.24 | 0.1369 | | 1.40 | 1.40 |
| 31-Aug-91 | 1 | GV9 | BDL | BDL | BDL | BDL | 0.00 | 0.28 | 0.25 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.20 |
| 27-Dec-91 | 141 | | BDL | BDL | BDL | BDL | | 0.30 | 0.30 |
| 09-Aug-91 | 1 | GV10 | BDL | BDL | BDL | BDL | 0.00 | 0.10 | 0.05 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.10 |
| 27-Dec-91 | 141 | | BDL | BDL | BDL | BDL | | 0.40 | 0.30 |

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 09-Aug-91 | 1 | GV11 | BDL | BDL | BDL | BDL | 0.00 | 0.25 | 0.15 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.20 |
| 04-Jan-92 | 149 | | BDL | BDL | BDL | BDL | | 0.40 | 0.40 |
| 09-Aug-91 | 1 | GV12 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 04-Jan-92 | 149 | | BDL | BDL | BDL | BDL | | 0.40 | 0.00 |
| 09-Aug-91 | 1 | GV13 | BDL | BDL | BDL | BDL | 0.00 | 0.00 | 0.00 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 04-Jan-92 | 149 | | BDL | BDL | BDL | BDL | | 0.15 | 0.10 |
| 09-Aug-91 | 1 | GV14 | BDL | BDL | BDL | BDL | 0.00 | 0.10 | 0.10 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.30 |
| 04-Jan-92 | 149 | | BDL | BDL | BDL | BDL | | 0.40 | 0.30 |
| 09-Aug-91 | 1 | GV15 | BDL | BDL | BDL | BDL | 0.00 | 0.15 | 0.10 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.30 |
| 04-Jan-92 | 149 | | BDL | BDL | BDL | BDL | | 0.40 | 0.30 |
| 09-Aug-91 | 1 | GV16 | BDL | BDL | BDL | BDL | 0.00 | 0.20 | 0.20 |
| 17-Oct-91 | 70 | | BDL | BDL | BDL | BDL | | | 0.20 |
| 04-Jan-92 | 149 | | BDL | BDL | BDL | BDL | | 0.30 | 0.20 |
| 09-Aug-91 | 1 | GV17 | 12.00 | 11.56 | 0.41 | 0.2369 | 0.16 | 2.80 | 2.50 |
| 17-Oct-91 | 70 | | 3.00 | 5.31 | 0.19 | 0.1083 | | 0.95 | 0.80 |
| 04-Jan-92 | 149 | | 5.00 | 6.70 | 0.24 | 0.1368 | | 1.40 | 1.30 |
| 10-Jul-91 | 1 | GV18 | 8.00 | 8.78 | 0.31 | 0.1797 | 0.17 | 3.30 | 2.05 |
| 09-Aug-91 | 31 | | 7.50 | 8.43 | 0.30 | 0.1732 | | 3.85 | 3.40 |
| 04-Jan-92 | 179 | | 7.00 | 8.08 | 0.29 | 0.1654 | | 2.10 | 1.80 |
| 10-Jul-91 | 1 | GV19 | 5.00 | 6.70 | 0.24 | 0.1368 | 0.13 | 2.30 | 1.20 |
| 09-Aug-91 | 31 | | 4.50 | 6.35 | 0.22 | 0.1304 | | | 3.40 |
| 08-Jan-92 | 183 | | 5.00 | 6.70 | 0.24 | 0.1368 | | 1.90 | 1.30 |
| 31-Aug-91 | 1 | GV20 | 4.00 | 6.00 | 0.21 | 0.1226 | 0.13 | 2.20 | 1.30 |
| 17-Oct-91 | 50 | | 4.50 | 6.35 | 0.22 | 0.1297 | | | 1.20 |
| 04-Jan-92 | 127 | | 4.50 | 6.35 | 0.22 | 0.1297 | | 1.40 | 1.20 |

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 31-Aug-91 | 1 | GV21 | BDL | BDL | BDL | BDL | 0.00 | 0.45 | 0.40 |
| 17-Oct-91 | 50 | | BDL | BDL | BDL | BDL | | | 0.30 |
| 04-Jan-92 | 127 | | BDL | BDL | BDL | BDL | | 0.30 | 0.20 |
| 29-Aug-91 | 1 | GV22 | BDL | BDL | BDL | BDL | 0.00 | 0.20 | 0.15 |
| 17-Oct-91 | 50 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 04-Jan-92 | 129 | | BDL | BDL | BDL | BDL | | 0.45 | 0.35 |
| 29-Aug-91 | 1 | GV23 | BDL | BDL | BDL | BDL | 0.00 | 0.10 | 0.10 |
| 17-Oct-91 | 50 | | BDL | BDL | BDL | BDL | | | 0.30 |
| 04-Jan-92 | 129 | | BDL | BDL | BDL | BDL | | 0.40 | 0.35 |
| 24-Aug-91 | 1 | GV24 | BDL | BDL | BDL | BDL | 0.00 | 0.10 | 0.10 |
| 17-Oct-91 | 50 | | BDL | BDL | BDL | BDL | | | 0.10 |
| 04-Jan-92 | 134 | | BDL | BDL | BDL | BDL | | 0.10 | 0.10 |
| 24-Aug-91 | 1 | GV25 | BDL | BDL | BDL | BDL | 0.00 | 0.10 | 0.10 |
| 17-Oct-91 | 50 | | BDL | BDL | BDL | BDL | | | 0.10 |
| 04-Jan-92 | 129 | | BDL | BDL | BDL | BDL | | | 0.10 |
| 26-Aug-91 | 1 | GV26 | BDL | BDL | BDL | BDL | 0.00 | 0.70 | 0.55 |
| 17-Oct-91 | 50 | | BDL | BDL | BDL | BDL | | | 0.50 |
| 04-Jan-92 | 129 | | BDL | BDL | BDL | BDL | | | 0.50 |
| 26-Aug-91 | 1 | GV27 | BDL | BDL | BDL | BDL | 0.00 | 0.20 | 0.15 |
| 17-Oct-91 | 53 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 04-Jan-92 | 132 | | BDL | BDL | BDL | BDL | | 0.35 | 0.30 |
| 26-Aug-91 | 1 | GV28 | BDL | BDL | BDL | BDL | 0.00 | 0.65 | 0.60 |
| 17-Oct-91 | 53 | | BDL | BDL | BDL | BDL | | | 0.60 |
| 04-Jan-92 | 132 | | BDL | BDL | BDL | BDL | | 0.35 | 0.30 |
| 26-Aug-91 | 1 | GV29 | 5.00 | 6.70 | 0.24 | 0.1369 | 0.12 | 2.50 | 1.40 |
| 17-Oct-91 | 53 | | 3.00 | 5.31 | 0.19 | 0.1083 | | | 0.90 |
| 04-Jan-92 | 132 | | 3.00 | 5.31 | 0.19 | 0.1083 | | 1.80 | 0.90 |
| 24-Aug-91 | 1 | GV30 | 3.10 | 5.38 | 0.19 | 0.1098 | 0.12 | 0.75 | 1.05 |
| 17-Oct-91 | 53 | | 3.50 | 5.65 | 0.20 | 0.1155 | | | 1.00 |
| 08-Jan-92 | 138 | | 4.00 | 6.00 | 0.21 | 0.1226 | | 1.30 | 1.10 |

| DATE | DAY | VENT ID# | FLOW (li/min) | CORRECTED FLOW (l/min) | FLOW (converted to cfm) | FLOW (SCFM) | AVERAGE FLOW (SCFM) | PRESSURE HEAD without flow (in. H2O) | PRESSURE HEAD with flow (in. H2O) |
|---|---|---|---|---|---|---|---|---|---|
| 24-Aug-91 | 1 | GV31 | BDL | BDL | BDL | BDL | 0.00 | 0.80 | 0.60 |
| 17-Oct-91 | 55 | | BDL | BDL | BDL | BDL | | 0.40 | 0.35 |
| 04-Jan-92 | 134 | | BDL | BDL | BDL | BDL | | 0.50 | 0.40 |
| 24-Aug-91 | 1 | GV32 | BDL | BDL | BDL | BDL | 0.00 | 0.55 | 0.50 |
| 17-Oct-91 | 55 | | BDL | BDL | BDL | BDL | | | 0.40 |
| 04-Jan-92 | 134 | | BDL | BDL | BDL | BDL | | | 0.40 |
| 24-Aug-91 | 1 | GV33 | BDL | BDL | BDL | BDL | 0.00 | 0.20 | 0.15 |
| 17-Oct-91 | 55 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 04-Jan-92 | 134 | | BDL | BDL | BDL | BDL | | | 0.00 |
| 24-Aug-91 | 1 | GV34 | BDL | BDL | BDL | BDL | 0.00 | 0.25 | 0.20 |
| 17-Oct-91 | 55 | | BDL | BDL | BDL | BDL | | | 0.20 |
| 04-Jan-92 | 134 | | BDL | BDL | BDL | BDL | | | 0.20 |
| 24-Aug-91 | 1 | GV35 | BDL | BDL | BDL | BDL | 0.00 | 0.20 | 0.15 |
| 17-Oct-91 | 55 | | BDL | BDL | BDL | BDL | | 0.00 | 0.00 |
| 04-Jan-92 | 134 | | BDL | BDL | BDL | BDL | | | 0.00 |

Appendix C

## Statistical Analysis

The average flow values for each of the measurable landfill vents were compared using the approximate t-test for independent samples with unequal variance as described by Ott (1988). Twenty-six vents were available for analysis. This analysis was made for compararison of the measureable flow rates from each vent, therefore, the BDL values were not considered. These data are presented in the tables below:

| | Average | Flows | (SCFM) |
|---|---|---|---|
| n | Active Section | 11-Acre Section | 30-Acre Section |
| 1 | 1.03 | 0.59 | 0.22 |
| 2 | 0.83 | 0.52 | 0.20 |
| 3 | 0.38 | 0.51 | 0.20 |
| 4 | - | 0.82 | 0.26 |
| 5 | - | 0.55 | 0.28 |
| 6 | - | 0.51 | 0.22 |
| 7 | - | 0.89 | 0.20 |
| 8 | - | 1.08 | 0.19 |
| 9 | - | 0.64 | 0.19 |
| 10 | - | 0.65 | - |
| 11 | - | 0.97 | - |
| 12 | - | 0.38 | - |
| 13 | - | 0.39 | - |
| 14 | - | 0.35 | - |

| | | | |
|---|---|---|---|
| n | 3 | 14 | 9 |
| mean | 0.7467 | 0.6321 | 0.2178 |
| std. dev. | 0.2718 | 0.2187 | 0.0301 |
| variance | 0.0739 | 0.0478 | 0.0009 |

Two different null hypotheses were tested. They were:

$$H_{o_1}: \mu_{active} - \mu_{11\text{-}acre} = D_o \tag{15}$$

$$H_{o_2}: \mu_{11\text{-}acre} - \mu_{30\text{-}acre} = D_o \tag{16}$$

where $\mu_i$ is the average flow for population i, and $D_o = 0$. The tests were run using probabilities of a type one error ($\alpha$) of 0.05 and 0.01 for 95% and 99% confidence intervals, respectively. The research hypotheses utilized were:

$$H_{a_1}: \mu_{active} - \mu_{11\text{-}acre} \neq D_o \tag{17}$$

$$H_{a_2}: \mu_{11\text{-}acre} - \mu_{30\text{-}acre} > D_o \tag{18}$$

The test statistic, t', was calculated using:

$$t' = \frac{\overline{y_1} - \overline{y_2} - D_o}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{19}$$

For the specified values of $\alpha$, $H_{o1}$ will be rejected if $|t'| > t_{\alpha/2}$, and $H_{o2}$ will be rejected if $t' > t_{\alpha}$.

Degrees of freedom were calculated using the following equations and rounded down to the nearest integer per Ott (1988):

$$df = \frac{(n_1 - 1)(n_2 - 1)}{(n_2 - 1)c^2 + (1 - c)^2 (n_1 - 1)} \tag{20}$$

where,

$$C=\frac{s_1^2/n_1}{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}} \tag{21}$$

The results of the analysis are given below:

| | $H_{o1}$ | $H_{o2}$ |
|---|---|---|
| t' | 0.6838 | 6.9869 |
| c | 0.8782 | 0.9714 |
| $c^2$ | 0.7712 | 0.9436 |
| df | 2 | 13 |
| $t_{.05}$ | 2.92 | 1.771 |
| $t_{.025}$ | 4.303 | 2.16 |
| $t_{.01}$ | 6.965 | 2.65 |
| $t_{.005}$ | 9.925 | 3.012 |

The values for $t_\alpha$ were taken from the t distribution tables in Ott (1988). From the results shown in the above, it was concluded that the average LFG flows, as measured from the gas vents, for the active and 11-acre sections were the same. The $H_{o1}$ two-tailed null hypothesis was accepted at the 99% confidence level. Furthermore, the 30-acre average flow values were less than and not equal to the 11-acre average flow values. The $H_{o2}$ single-tailed null hypothesis was rejected at the 99% confidence level.

# Appendix D

## Scholl Canyon Model

There is no available data to determine which analytical model is the most suitable for landfill gas kinetics. For the purposes of this project, one model was selected and utilized. Other methods may also be considered as reasonable tools for gas production estimations.

The Scholl Canyon model is a model of substrate-limited microbial growth. It assumes that there is a negligible lag time during which anaerobic conditions are established, the microbial population is built up and stabilized, and the gas production rate reaches its peak (Schumacher 1983). It is assumed that the gas generation rate decreases as the organic fraction of the MSW is diminished. The landfill is unable to support the ever decreasing biomass of gas-producing organisms and the population crashes.

In the Scholl Canyon analysis, the refuse mass is broken down into sub-masses, which were placed during each year of the landfills operation. The subscript i denotes values for the sub-mass i. The expression for the composite gas production rate at a point in time is given as follows (Schumacher 1983):

$$kL=\sum_{i=1}^{n} r_i k_i L_{o_i} e^{-k_i t_i} \tag{22}$$

where,

$t_i$ = the time from placement of each refuse sub-mass,

$r_i$ = the ratio of the weight of each sub-mass to the total of the total refuse weight,

$L_o$ = total volume of methane ultimately to be produced (from stoichiometric analysis),

k = rate constant

To determine the value of $k_i$, the following equation given by Schumacher (1983) was utilized:

$$k_i = \frac{\ln(\frac{G}{G_o})}{t_{1/2}} \tag{23}$$

where, G = volume of gas produced prior to time t.

Substituting in the assumed values $G_o = L_o/100$ and $G = L_o/2$ for the assumed half-life $t_{1/2}$ of the organic wastes, per Schumacher (1983), the equation may then be written as follows:

$$k_i = \frac{\ln(50)}{t_{1/2}} \tag{24}$$

Baubeau (1990) states that half-lives for readily degradable wastes (mostly food wastes) is one year, while the $t_{1/2}$ value of moderately degradable wastes (cellulose wastes such as grass, wood, paper, cardboard, and textiles) ranges between 2 to 15 years. Refractory wastes, such as rubber or plastics, have half-lives in excess of 20 years.

The values for the sub-masses were provided by Mr. Bo Bruner of CH2M-Hill and Mr. Tim Townsend of the University of Florida, Department of Environmental Engineering. These values are shown in table D-1. Projections of future refuse disposals for the active section were based on an average of 10,000 tons per month.

The resultant graphs for this analysis are provided in Chapter 5. Schumacher (1983) states that there are no guarantees that the Scholl Canyon approach will accurately estimate the time dependency of landfill gas production. Many other environmental factors may

be rate limiting within the landfill with regard to the bacterial growth..

| | Tons of Refuse | | |
|---|---|---|---|
| Year | 30-acre | 11-acre | active |
| 1972 | 60256 | 0 | 0 |
| 1973 | 73944 | 0 | 0 |
| 1974 | 79632 | 0 | 0 |
| 1975 | 85320 | 0 | 0 |
| 1976 | 91008 | 0 | 0 |
| 1977 | 96696 | 0 | 0 |
| 1978 | 102384 | 0 | 0 |
| 1979 | 108072 | 0 | 0 |
| 1980 | 113760 | 0 | 0 |
| 1981 | 119448 | 0 | 0 |
| 1982 | 125136 | 0 | 0 |
| 1983 | 130824 | 0 | 0 |
| 1984 | 136512 | 0 | 0 |
| 1985 | 0 | 156370 | 0 |
| 1986 | 0 | 126815 | 0 |
| 1987 | 0 | 126815 | 0 |
| 1988 | 0 | 0 | 96173 |
| 1989 | 0 | 0 | 119987 |
| 1990 | 0 | 0 | 124322 |
| 1991 | 0 | 0 | 119600 |
| 1992 | 0 | 0 | 120000 |

Table D-1: Annual Refuse Disposal Per Year for ACSWL

## REFERENCES


Barlaz, M.A., D.M. Schaefer, and R.K. Ham, 1989. "Bacterial Population Development and Chemical Characteristics of Refuse Decomposition in a Simulated Sanitary Landfill," Applied and Environmental Microbiology, Vol. 55, No. 1.

Barlaz, M.A., R.K. Ham, and D.M. Schaefer, 1990. "Methane Production From Municipal Refuse: A Review of Enhancement Techniques and Microbial Dynamics," Critical Reviews in Environmental Control, Vol. 19, Issue 6.

Baubeau, P.L., M. Heguy, and J. Gitton, 1990. "Biogas From Municipal Landfills," Energy from Biomass and Wastes XIII. D.L. Klass, ed., Institute of Gas Technology, Chicago.

Brown, G.G., et al, 1953. Unit Operations, John Wiley & Sons, Inc., New York.

Buivid, M.G., 1981. "Fuel Gas Enhancement by Controlled Landfilling of Municipal Solid Waste," Resour. Recovery Conserv., Vol. 6, No. 3.

Burghardt, M.D., 1982. Engineering Thermodynamics with Applications, Second Edition, Harper & Row, Inc., New York.

Clark, W.E., 1964. Water Resources of Alachua, Bradford, Clay, and Union Counties, Florida. R.I. No. 35. Florida Department of Natural Resources. Tallahassee.

CH2M-Hill and Environmental Science and Engineering 1986. Volume 1: Contamination assessment report, Southwest Landfill, Alachua County, Florida. Prepared for Alachua County Department of Public Works, Gainesville.

Cheremisinoff, P.N., and A.C. Morresi, 1976. Energy from Solid Wastes. Marcel Dekker, Inc. New York.

Chian, E.S.K. and F.B. DeWalle, 1979. "Effect of moisture regimes and temperature on MSW stabilization," Proceedings of the Fifth Annual Research Symposium, Municipal Solid Waste: Land Disposal. EPA-600/9-79-023.

DeWalle, F.B., E.S.K. Chian, and E. Hammerburg, 1978. "Gas Production from Solid Waste in Landfills," Journal of Environmental Engineering, ASCE. Vol. 104, EE3.

Dwyer, D., 1992. "Analysis of Landfill Gas Quality at the Alachua County Southwest Landfill Site," ME Thesis, University of Florida.

Esmaili, H., 1975. "Control of Gas Flow from Sanitary Landfills," Journal of the Environmental Engineering Division - ASCE. Vol. 101, Issue 4.

EMCON Associates, 1980. State of the Art of Methane Gas Enhancement in Landfills, San Jose.

Farquhar, G.F. and F.A. Rovers, 1973. "Gas Production During Refuse Decomposition," Water, Air, and Soil Pollution, Vol. 2.

Findikakis, A.N. and J.O. Leckie, 1979. "Numerical Simulation of Gas Flow in Sanitary Landfills," Journal of the Environmental Engineering Division - ASCE. Vol. 105, Issue 5.

Findikakis, A.N., P. Papelis, C.P. Halvadakis, and J.O. Leckie, 1988. "Modelling Gas Production in Managed Sanitary Landfills," Waste Management Res.. Vol. 6, No. 115.

Florida Department of Environmental Regulation, 1991. Solid Waste Management in Florida: 1990 Annual Report. FDER, Tallahassee.

Franklin Associates, 1988. Characterization of Municipal Solid Waste in the United States 1960-2000 (Update 1988). EPA/530-SW-88-033, U.S. Environmental Protection Agency, Washington D.C.

Ham, R.K., K.K. Hekimian, S.L. Katten, W.J. Lockmans, R.J. Lofy, D.E. McFaddin, and E.J. Daley, 1979. "Recovery, Processing, and Utilization of Gas From Sanitary Landfills," EPA-600/2-79-001, February.

Ham, R.K. and M.A. Barlaz, 1989. "Measurement and Prediction of Landfill Gas Quality and Quantity," Sanitary Landfilling: Process Technology, and Environmental Impact. T.H. Christensen, R. Cossu, and R. Stegmann, eds., Academic Press, Orlando.

Ham, R.K., and T.J. Bookter, 1982. "Decomposition of Solid Waste in Test Lysimeters," Journal of Environmental Engineering, ASCE. Vol. 108, EE6.

Laquidara, M.J., A.P. Leuschner, and D.L. Wise, 1986. "Procedure for Determining Potential Gas Quantities in an Existing Sanitary Landfill," Water Science and Technology. Vol. 18, No. 12.

Lily, P.E., R.C. Reid, E. Buck, 1984. "Physical and Chemical Data," Perry's Chemical Engineers' Handbook, 6th ed., R.H. Perry and D.W. Green, eds., McGraw-Hill Book Co., New York.

Lu, A. and C.O. Kunz, 1981. "Gas-Flow Model to Determine Methane Production in Sanitary Landfills," Environmental Science and Technology, Vol. 15, No. 5.

Miller, W.L., J.F.K. Earle, T.G. Townsend, C.W. Bartlett, and H. Lee, 1991a. "Leachate Recycle and the Augmentation of Biological Decomposition at Municipal Solid Waste Landfills," Report No. 91-3, State University System of Florida Center For Solid and Hazardous Waste Management, Gainesville.

Miller, W.L., T.G. Townsend, J.F.K. Earle, R.J. Bruner, and E.E. Culpepper, 1991b. "Developing Tomorrow's Landfill: The Alachua County Southwest Landfill Research Project." Presented at the Third Annual Southeastern Regional Solid Waste Symposium, Solid Waste Association of North America, Orlando, Nov. 5-7, 1991.

Ott, L., 1988. An Introduction to Statistical Methods and Data Analysis. PWS-Kent Publishing Co., Boston.

Pacey, J., 1976. "Methane Gas in Landfills: Liability or Asset?", Proc. Fourth National Congress on Waste Management Technology and Resource and Energy Recovery, EPA report SW-8p.

Pohland, F., 1986. "Critical Review and Summary of Leachate and Gas Production From Landfills," EPA-600/2-86/073, February.

Porter, W.J., 1988. "Is the Nation Entangled in a Solid Waste Crisis," Waste Age. Vol.19, No. 4, April.

Ramaswamy, J.N., 1970. "Nutritional Effects on Acid and Gas Production in Sanitary Landfills," Ph.D. Thesis, West Virginia University.

Rhyne, C.W. and S.C. James, 1978. "Methane Production, Recovery, and Utilization from Landfills," Energy from Biomass and Wastes. Institute of Gas Technology, Chicago.

Rice, F.C., 1989. "Monitoring and Managing Landfill Gas," Proceedings from the First Annual Southeastern Regional Solid Waste Symposium, Savannah, Georgia, October 11-13.

Sakiadis, B.C., 1984. "Fluid and Particle Mechanics," Perry's Chemical Engineers' Handbook, 6th ed., R.H. Perry and D.W. Green, eds., McGraw-Hill Book Co., New york.

Schumacher, M.M., 1983. Landfill Methane Recovery, Noyes Data Corporation, Park Ridge, New Jersey.

Songonuga, O.O.O., 1970. Ph.D. Thesis, West Virginia University.

Sproul, C.R., 1986. Technical Memorandum to Florida Department of Environmental Regulation - Northeast District. Proposed revisions to the Lake Alice groundwater monitoring program. CH2M-Hill, Gainesville.

Straka, F., 1990. "Evaluation of Landfill Gas Recovery Sites with a Mobile Pumping System," Energy from Biomass and Wastes XIII. D.L. Klass, ed., Institute of Gas Technology, Chicago.

Tchobanoglous, G., H. Theisen, and P. Eliassen, 1977. Solid Wastes: Engineering Principles and Management Issues, McGraw-Hill Book Co., New York.

TIA Solid Waste Management Consultants, Inc., 1991. Alachua County Waste Composition Study. Prepared for Alachua County Board of County Commissioners, November.

Vennard, J.K., and R.L. Street, 1975. Elementary Fluid Mechanics, Fifth Edition, John Wiley & Sons, New York.

Weast,R.C. and M.J. Astle, eds., 1982. CRC Handbook of Chemistry and Physics. CRC Press, Inc., Boca Raton.

White, W.A., 1970. The Geomorphology of the Florida Peninsula. Geological Bulletin No. 51. Florida Department of Natural Resources. Tallahassee.

Wolfe, B., 1990. "Commercial Landfill Gas Recovery Operations - Technology and Economics," Energy From Biomass and Wastes XIII. D.L. Klass, ed., Institute of Gas Technology, Chicago.

Thesis
M27974 Manley
c.1 Alachua County Southwest
Landfill gas production
as a function of time.